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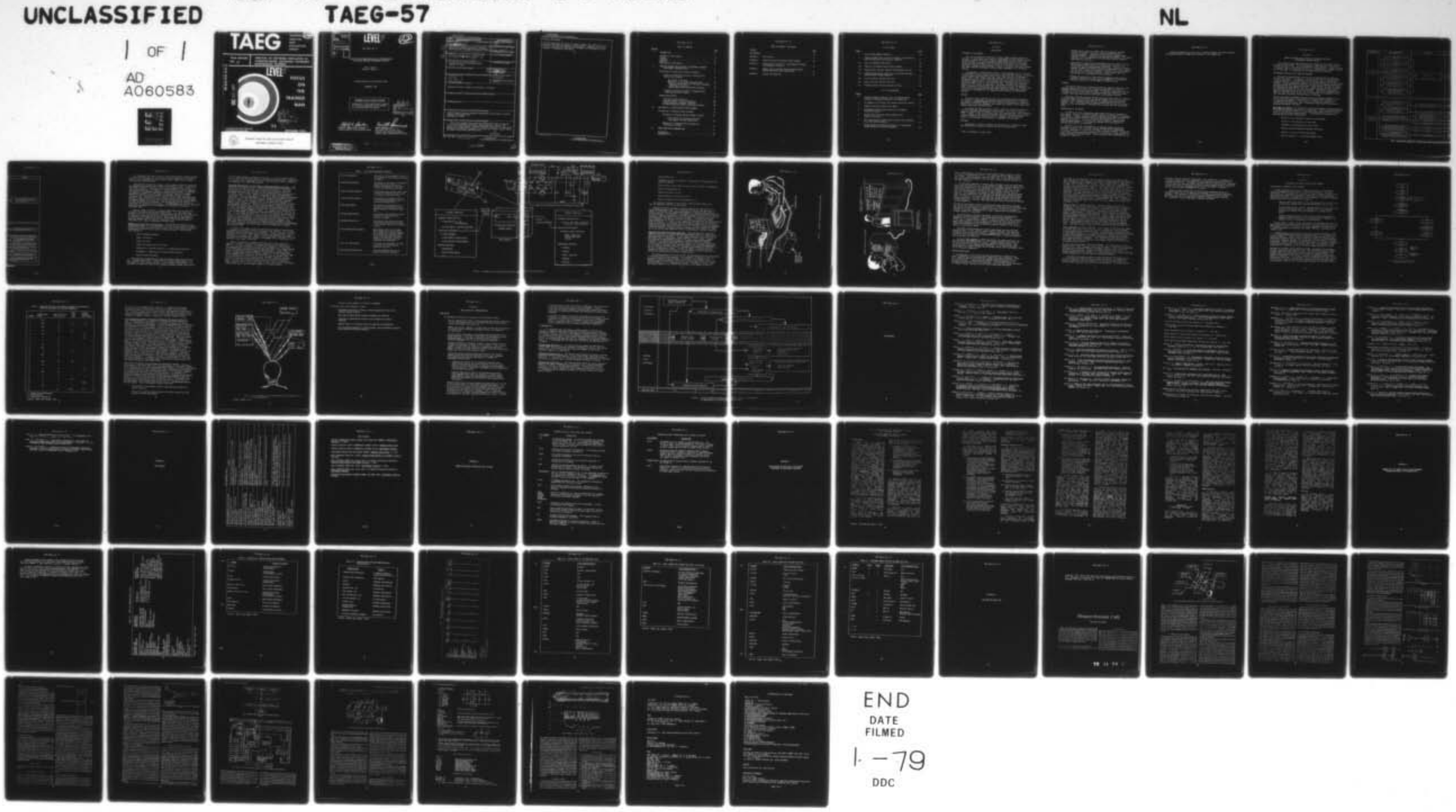

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TRAINING ANALYSIS AND EVALUATION GROUP

TAEG REPORT NO. 57

ANALYSIS OF SOFTWARE SIMULATION IN COMPUTER-BASED ELECTRONIC EQUIPMENT MAINTENANCE TRAINERS

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TAEG Report No. 57

ANALYSIS OF SOFTWARE SIMULATION IN COMPUTER-BASED ELECTRONIC EQUIPMENT MAINTENANCE TRAINERS

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September 1978

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This study assessed the current and future application of computers in electronic equipment maintenance training devices. Emphasis was placed on examining computer software simulation techniques for generating emulations of electronic equipment front panel and internal circuit static and dynamic operational characteristics.

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Abstract (continued)

The report does not present a formal review of the state-of-the-art in electronic equipment maintenance training devices. However, much of the relevant literature was organized and reviewed; a bibliography of source documents is appended to the report.

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INTRODUCTION

STATEMENT OF THE PROBLEM

The use of electronics technology in modern weapon systems continues to increase. To meet operational readiness requirements for these weapons systems, the Naval Education and Training Command (NAVEDTRACOM) annually trains over 50,000 personnel in formal electronic equipment maintenance training courses. Maintaining the effectiveness and efficiency of these courses is a constant challenge. Because of this challenge, a merger of synthetic simulation concepts with new electronic maintenance training support equipment is of increasing concern.

Unfortunately, an appropriate interest in the widespread use of simulation in maintenance training, either electronic or other, has been lacking. A previous Training Analysis and Evaluation Group (TAEG) study (Pearson, Mac Keraghan, Stubbs, Moore, 1974a, 1974b) found that interest in the use of simulation for maintenance training exists at the working level but is difficult to elicit at the decision making levels. This dichotomy was articulated in a Chief of Naval Operations (CNO)[1] letter to the Director of TAEG. The CNO letter expressed concern over the future of simulation in maintenance training and requested TAEG's assistance in developing a near-term course of action. In response, the Chief of Naval Education and Training (CNET) approved a TAEG study to assess the status of and potentials for computer-based simulation for maintenance trainers.

PURPOSE

The goal of this study was to assess the current and future applications of computers in electronic equipment maintenance training devices. Emphasis was placed on examining computer software simulation techniques for generating emulations of electronic equipment front panel and internal circuit static and dynamic operational characteristics.

No attempt was made to present a formal review of the state-of-the-art in electronic equipment maintenance training devices. This story is told in a number of reports (see, for example, Brock, 1978; King and Duva, 1975; Montemerlo, 1977). However, in the course of achieving the study objectives, much of the relevant literature has been organized and reviewed. For the interested reader, a bibliography of these sources is appended to this report.

RATIONALE

Examination of computer software simulation for use in electronic equipment maintenance training was selected for the following reasons:

[1] CNO ltr OP-0991B of 4 August 1976.

- Computer-based simulation (widely applied in operator training devices) has numerous advantages over using hardware-based training equipments. Improved personnel safety, reduced system alignment problems, adaptability to changing requirements, and reduced ownership costs are important attributes often favoring computer-based simulation devices.

- Development of computer-based maintenance training devices lags far behind computer-based operator training devices in spite of an increasingly sophisticated computer technology. Advances in digital computer hardware and software continue at exponential rates, reducing cost per unit of memory and computer size while increasing the power and flexibility of software programs. These advances should be capitalized on for maintenance training devices.

- Widespread application of cost-effective computer-based electronic equipment maintenance training devices (EEMTDs) has a potentially large cost benefit due to the number of potential users.

APPROACH

The current literature on maintenance training, computer simulation, and computer-aided design of electronics equipments pertinent to electronics equipment software simulation was reviewed. The approach taken was to use the literature as a source for developing generalizations and predictions about software simulation applications in electronics maintenance training.

Additional data were obtained through discussions with experts in computer-based maintenance training devices and computer-aided design of electronic equipment. Much information was obtained via telephone conversations with experts. Also, a selected number of subject-matter experts were visited (see appendix A) for the purposes of reviewing their current work and to exchange ideas.

ORGANIZATION OF THE REPORT

In addition to this introduction, three other sections are presented in this report. Section II discusses computer software in current use in computer-based EEMTDs. Software programs typical of computer-based EEMTDs are described and significant factors that have influenced the characteristics of these programs are detailed. A critique of the current status of computer-based EEMTD software programs is also presented together with descriptions of computer-based EEMTDs, by categories.

Section III discusses the potentials of computer software simulation technology currently used to design, develop, and manufacture operational electronic equipments as a new source of EEMTD simulation software. An overview is provided of design automation software and the relevance of this software to EEMTD, including an applied example. Study conclusions and recommendations are presented in section IV.

Supportive materials on data sources, computer managed instruction software, and design automation software are contained in five appendices.

SECTION II

COMPUTER SOFTWARE APPLICATIONS IN ELECTRONIC EQUIPMENT MAINTENANCE TRAINING DEVICES

This section of the report discusses the current use of software programs in computer-based EEMTD. In its development, a conscious effort was made to minimize the use of often confusing technical jargon and terms. Where inclusion of technical data was considered necessary, it is presented in a manner intended to aid the reader in conceptualizing and understanding the material.

MAINTENANCE TRAINING DEVICE COMPUTER PROGRAMS

The generic programs found to be typical of state-of-the-art EEMTD are presented in figure 1. The purpose, use, and typical users of these programs are also identified. The programs are separated into the two conventional categories used by the computer industry: (1) system programs and (2) application programs. System programs are generally developed by the computer manufacturer and supplied with each computer purchased. These programs are used to support the operation and maintenance of the basic computer system and were, therefore, not considered relevant to the study objectives. Application programs are generally developed by the user of the computer. Application programs perform specific functions related to the task(s) the computer is performing for the user, and were, therefore, the major focus of the study.

FACTORS INFLUENCING MAINTENANCE TRAINING DEVICE APPLICATIONS PROGRAMS. Three factors have influenced the characteristics of applications programs used in computer-based EEMTDs: (1) new trends in training, (2) advances in instructional delivery media, and (3) simulation requirements for electronic equipment maintenance job tasks.

New Trends in Training. An increasingly employed educational strategy emphasizes individual abilities and flexibility in instruction. Individualized instruction is defined in CNETINST 1500.12 as "Instruction that attends to the individual needs of and differences among students." Individualized instruction can be characterized in the following ways:

- tailored to the individual student's training needs
- allows for self-pacing by the individual
- adjustable to individual entry skill levels
- employs criterion-referenced measures of mastery
- permits a variety of instructional media
- does not require a 1:1 instructor/student ratio.

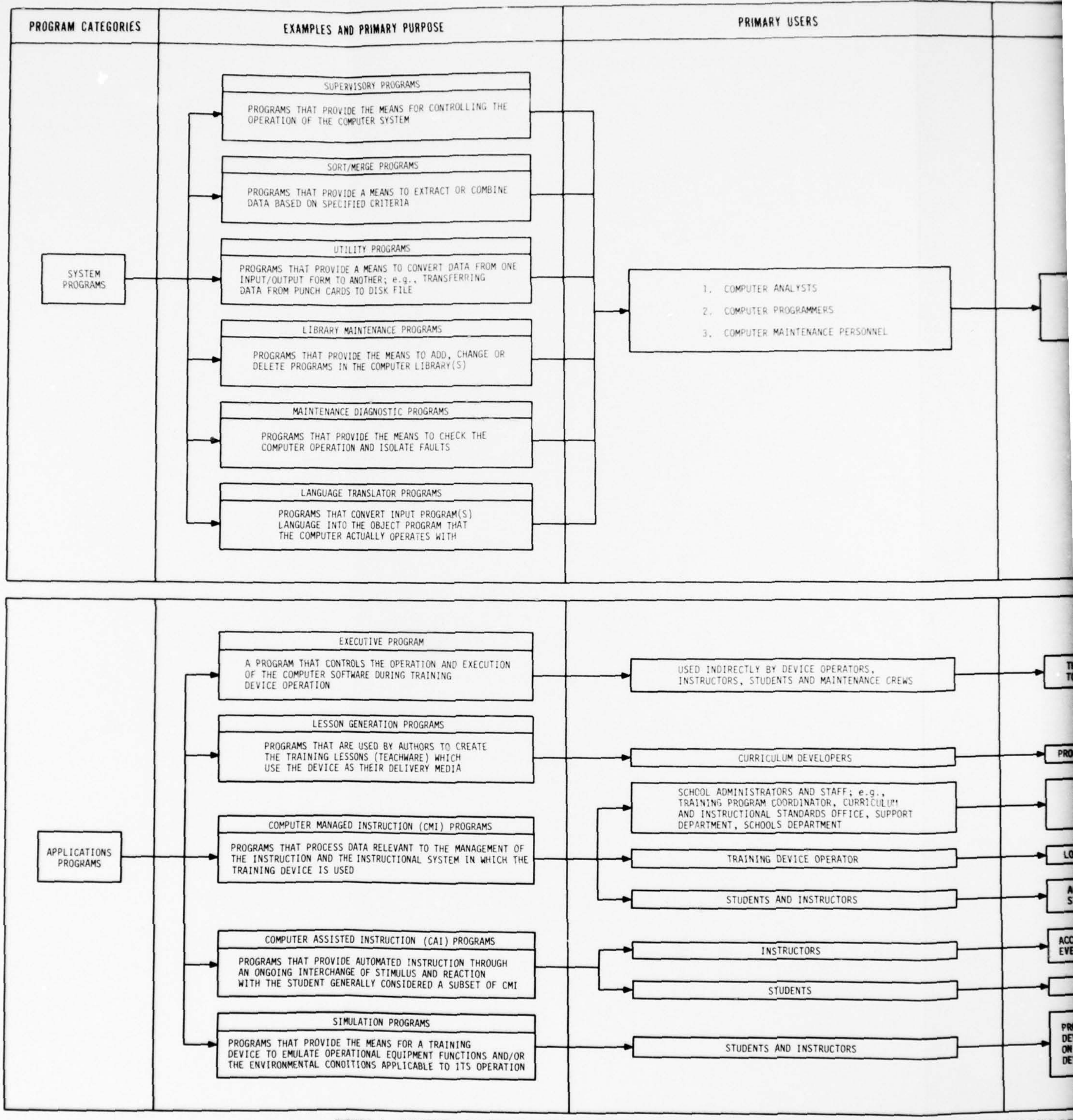


FIGURE 1. COMPUTER SOFTWARE PROGRAMS TYPICAL OF COMPUTER BASED ELECTRONIC EQUIPMENT MAINTENANCE TRAINING DE

PRIMARY USE

OPERATING SYSTEMS PROGRAMS (GENERALLY PROVIDED BY THE COMPUTER MANUFACTURER) ARE USED TO MORE EFFICIENTLY AND EFFECTIVELY APPLY THE COMPUTER TO MEET THE NEEDS OF THE USER.

THIS PROGRAM PROVIDES THE MEANS FOR EACH DEVICE USER TO FUNCTIONALLY PERFORM HIS RESPECTIVE TASK

PROGRAM USED TO CREATE, DELETE, MODIFY TRAINING LESSONS

PROGRAM TO AID MANAGEMENT OF THE TRAINING PROGRAM; e.g., CURRICULUM MANAGEMENT, QUALITY ASSURANCE, LOGISTICS SUPPORT, MAINTAINING ACADEMIC RECORDS, STUDENT SCHEDULES

LOGISTICS ON DEVICE; e.g., AVAILABLE TRAINEE STATIONS

ACCESS TO STUDENT/CURRICULUM DATA; e.g., PERFORMANCE, STUDENT SCHEDULES, CURRICULUM CONTENT

ACCESS TO/INTERACTION WITH LESSON INTERNAL INSTRUCTIONAL EVENTS

PRIMARY MEANS OF TRAINING LESSON INSTRUCTION

PROVIDES FOR STUDENT INTERACTION WITH THE TRAINING DEVICE IN A MANNER SIMILAR TO INTERACTIONS ACCOMPLISHED ON THE ACTUAL EQUIPMENT THAT THE TRAINING DEVICE EMULATES

TRAINING DEVICES

For individualized instruction, the instructional material and the methods of instructional delivery are so designed that each student is led through the material with intervention by the instructor only in cases where a student experiences extreme difficulty.

Individualized instruction, however, has the adverse effect of increasing the management and administrative burden of the school's staff. Scheduling of facilities, students, instructors, and training equipment is but one area significantly impacted. The computer is ideally suited to handling management and administrative problems induced by individualized training. In addition, the computer is capable of providing an interactive learning environment wherein the computer software programs are designed to play a surrogate instructor role. Recognition of the computer's value in both training management and in controlling the delivery of instruction has led to the development of computer managed instruction (CMI) application programs with subset computer assisted instruction (CAI) programs. The CAI programs provide interactive instruction for individualized training. "The NAVEDTRACOM has the most successful application of computers to the management of instruction in the world ...." (Scanland, 1978).

Training research interest in computer based EEMTDs and the application of CMI/CAI in training have occurred concurrently. It is not surprising, therefore, that most state-of-the-art EEMTDs possess CMI and/or CAI capabilities. In some cases, combining simulation with CMI/CAI has been at the expense of the training tasks taught on the device. Major emphasis has been placed on providing sophisticated CMI and CAI programs with less attention given to installing a full range of maintenance training tasks.

<u>Advances in Instructional Delivery Media</u>. State-of-the-art advances in many technological areas; e.g., microelectronics, microfilm, and audio/visual record/playback technology and visual display systems, have created rapidly expanding improvements in audio/visual instructional delivery media. These advances have resulted in:

- smaller hardware packaging
- higher reliability
- lower unit costs
- higher data density per unit volume
- automation of functional controls via computer/micro-processor
- programmed or random access to instructional materials
- student interactive media.

The attributes listed above have made audio/visual media attractive for use in computer-based EEMTD. State-of-the-art computer-based EEMTDs utilize one or more of these new media options in the simulator configurations. In the EEMTD, the media are controlled by computer software programs that perform

the role (among others) of resource allocation; i.e., as the student interacts with an EEMTD, the available media are activated and controlled by a computer(s). In the strict sense, the computer programs that provide the control capability are components of an EEMTD CMI function.

Simulation Requirements for Electronic Equipment Maintenance Job Tasks. TAEG Report No. 9-2 (Pearson, et al., 1974b) identified tests and measurements as a major job function performed by the maintenance technician. Tests and measurements are the principal means by which the maintenance technician determines the operational integrity of the equipment and are the major basis for making repairs. Table 1 defines categories of tests and measurements identified as job task requirements for electronic warfare equipment maintenance technicians. Tests and measurements may be conducted using general purpose, special purpose, or built-in test equipment including diagnostic computer programs. Additionally, component parts of the operational equipment; e.g., meters, lamps, displays, are often utilized as test and measurement indicators by maintenance technicians. The tests and measurements produce results that the technician compares against known standards for the equipment under test in order to determine appropriate preventive or corrective maintenance actions; e.g., realign, replace, remove, or repair. As a general rule, the results of a test or measurement are observed by the maintenance technician in one of two ways: (1) as a numerical value (e.g., 10 volts, 5 kilowatts, 750,000 ohms) or (2) as a visual representation of the property being examined (e.g., a current waveform, a voltage waveform, a frequency spectrum) from which numerous other properties can be determined, such as amplitude, period, frequency. The newer, more sophisticated electronic equipment and test equipments provide more simple "go/no go" indications for a large spectrum of tests and measurements. Any of the observable test results may be static (nonchanging) or dynamic (varying with time).

To allow a full range of test and measurement maintenance training tasks to be taught via simulated electronic equipment, both "external" and "internal" equipment component functions must be simulated. External component functional simulation (as defined by TAEG) emulates functions of equipment front panel components; e.g., knobs, dials, lamps. Internal equipment functional simulation (as defined by TAEG) emulates functions of equipment circuit components; e.g., amplifiers, oscillators, rectifiers.

Figure 2 illustrates an example of external and internal simulation problems. As shown in figure 2 the external simulation requirement for the EEMTD is to create an emulation of a meter panel operation. A maintenance task requiring this simulation involves the trainee observing a voltage reading on the EEMTD Regulation Panel output voltage meter (M1). If the voltage is higher or lower than the system requires, the maintenance technician must adjust a potentiometer (R8 on the panel in figure 2). If the voltage reading can be adjusted within tolerance, the technician could go to other tasks. If in this situation the trainee can not adjust the meter reading to required tolerance, he may decide to troubleshoot the circuits associated with the meter. For this task, internal simulation would be required. Assuming no output voltage; that is, the circuit shown in figure 2 has a fault, the trainee might perform any of the following procedures in a random fashion:

TABLE 1. TEST AND MEASUREMENT CATEGORIES

Basic Measurements	Those tests and measurements that can be conducted on any electronic warfare equipment.
Waveform Measurements	Pertaining to the shape of an electromagnetic/electrical wave or its graphic representation, showing the variation in amplitude with time.
Sensitivity Measurements	Pertaining to the minimum signal input required to produce an output signal or response at specified value.
Selectivity Measurements	Pertaining to the degree or ability to differentiate between signals of different characteristics.
Power Measurements	Pertaining to the determination of the rate of transferring or transmitting energy in electronic equipment.
Frequency Measurements	Pertaining to the repetitive characteristics of signals that are periodic in nature.
Impedance Measurements	Pertaining to the total resistance (resistance and reactance) to electrical current flow in an AC current circuit.
Servo Mechanism Measurements	Measurements relative to systems which respond to a control signal and in which the difference between the desired state and the actual state is fed back into the control system until continued response eliminates the difference.
Logic Unit Measurements	Pertaining to measurements in those electronic units that perform reasoning functions.
Miscellaneous Measurements	Those measurements that are not placed in any other category.

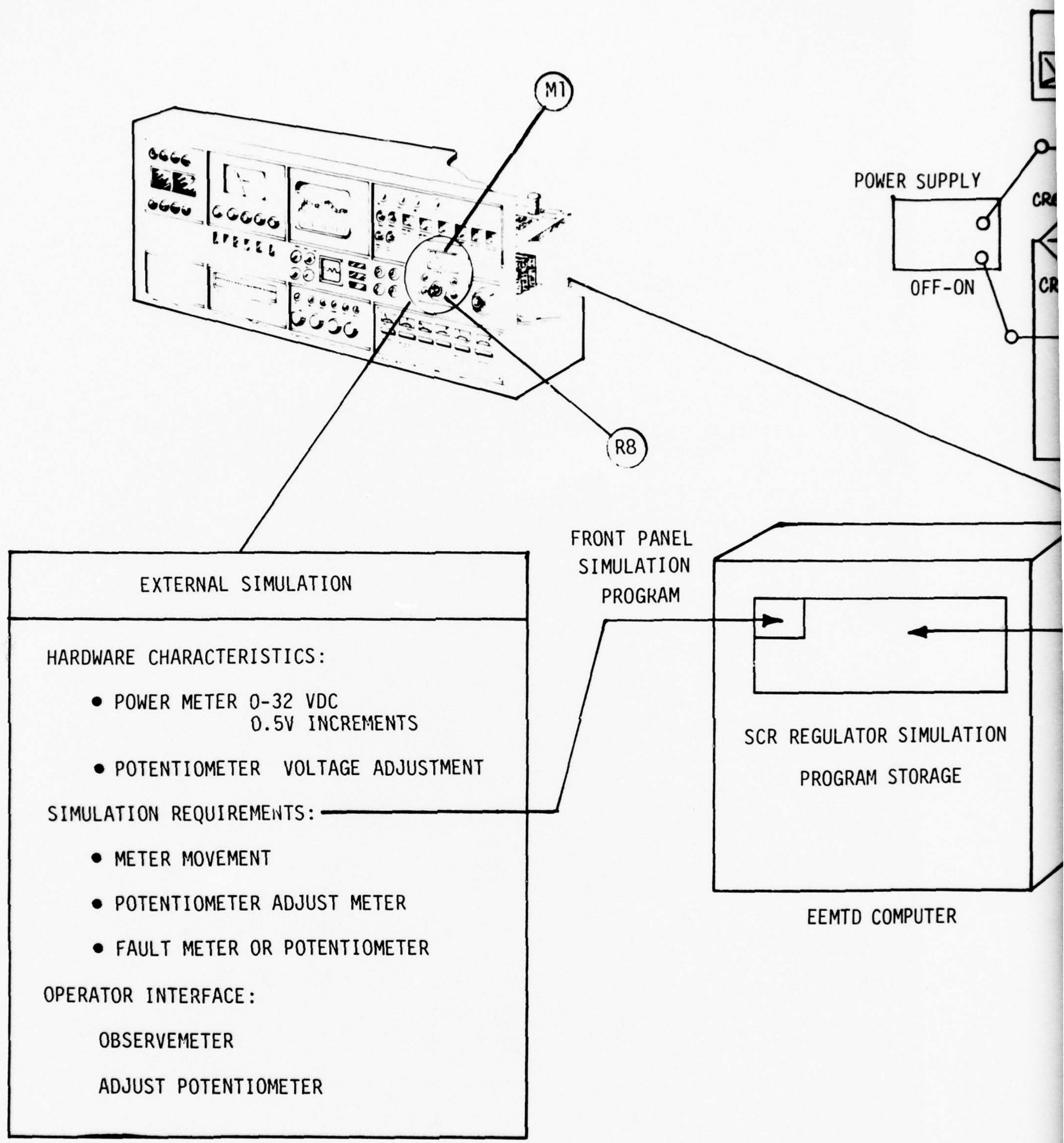
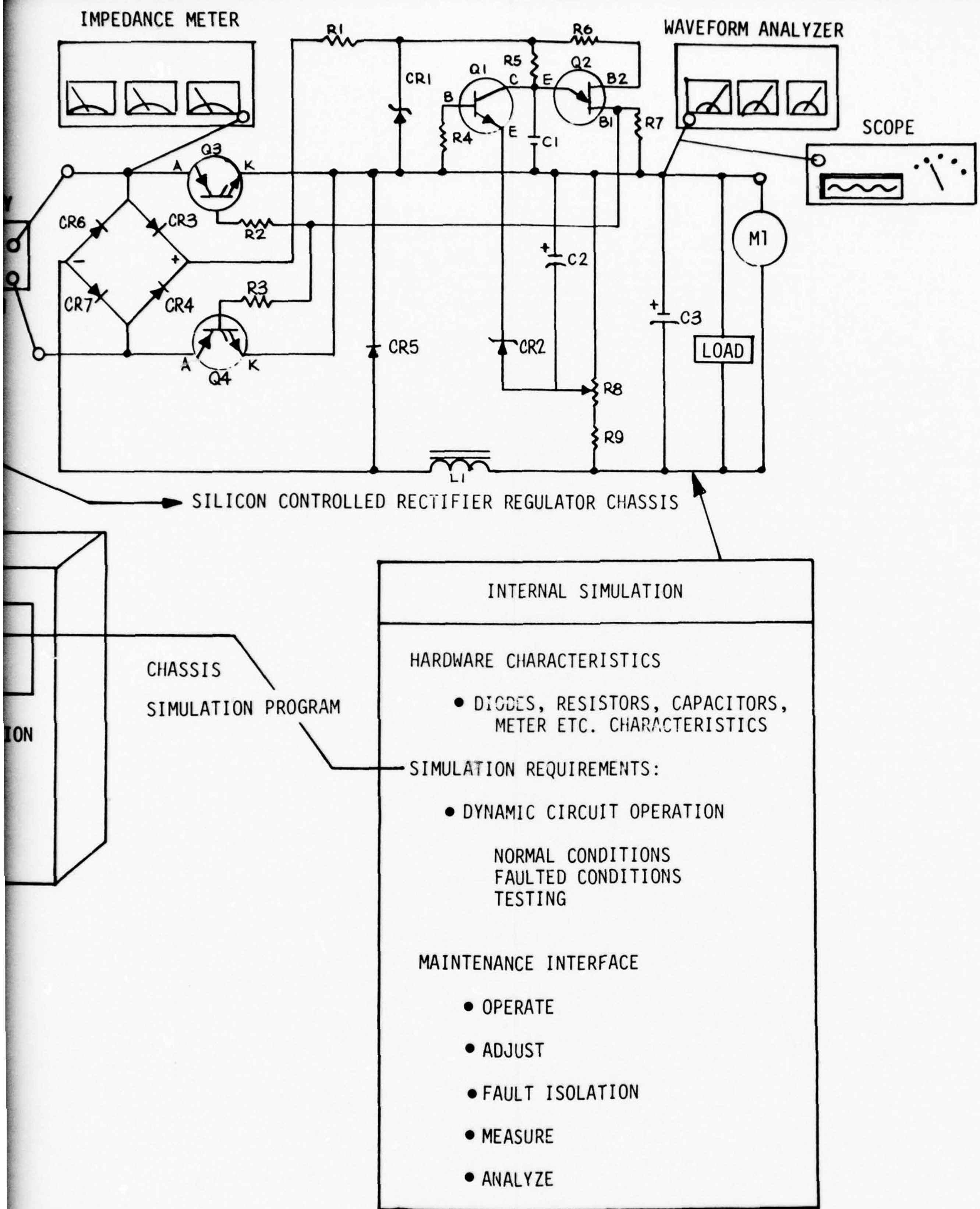


Figure 2. Examples of an Internal and External Sim



nal Simulation Problem

- check primary fuse
- determine, with an oscilloscope, if there was a firing pulse at the gate of Q3 and Q4
- check control circuit (Q1) for fault or R2, R3 and R7 for operation
- measure voltage across CR1
- check CR3 and CR4, R1, CR1
- check voltage at C1 and base 2 of Q2
- check resistance of L1 and capacitance of C1.

The simulator response to the trainee's probing should appear to be real for beneficial learning to take place.

External electronic equipment functions emulated via simulation is a highly developed technology. This technology has evolved over many years of research, development, and widespread deployment of computer-based operator training devices. Though complex, requirements for external equipment simulation are not as technically demanding as internal equipment simulation. For external simulation, the requirements can be well defined. For internal simulation, the requirements are much more difficult to define. Transient and steady state combinations of internal circuit conditions observable during troubleshooting could be infinite. To illustrate the differences in complexity, the relative memory storage needs for computer programs to simulate the external and internal situations discussed above are shown in figure 2. Internal electronic equipment simulation presents an imposing problem to researchers and producers of EEMTD and as yet has not been adequately solved through computer software simulation.

Computer-Based EEMTD Simulation Techniques. There are two basic simulation approaches utilized to re-create test and measurement results in operationally deployed computer-based EEMTD. The most common technique is to store test and measurement data in photographic format (generally color slides). The data are generated by photographing sequences of actual tests and measurements conducted on the operational equipment for which the EEMTD will provide training. Subsequently, when the student conducts or is provided instruction on the conduct of specific tests and measurements, the prestored photographic data is displayed on EEMTD projection equipment thus providing a simulation of the test or measurement results. As shown in figure 3, activation of the projection system(s) and selection of the appropriate picture or sequence of pictures are controlled by the EEMTD computer system.

The second approach to re-creating test and measurement data has similarities to the photographic format approach. The fundamental difference is that the operational equipment static parametric test data; e.g., numeric values, waveforms, go/no go indicators, are stored in digital data format in the EEMTD computer memory in lieu of photographic storage. As shown in figure 4, when the student conducts or is provided instruction on the conduct of specific

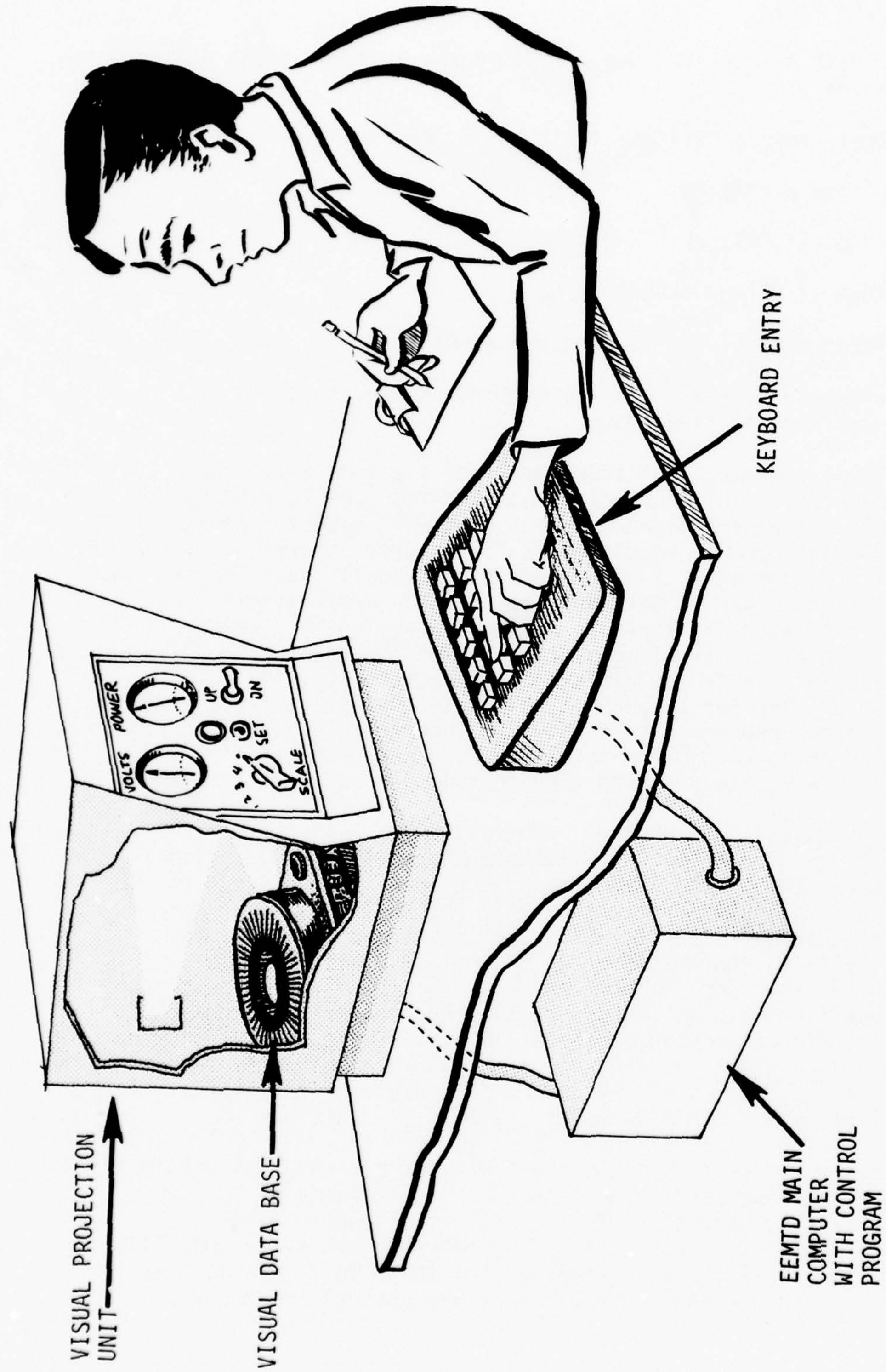


Figure 3. Computer Controlled Audio/Visual Media

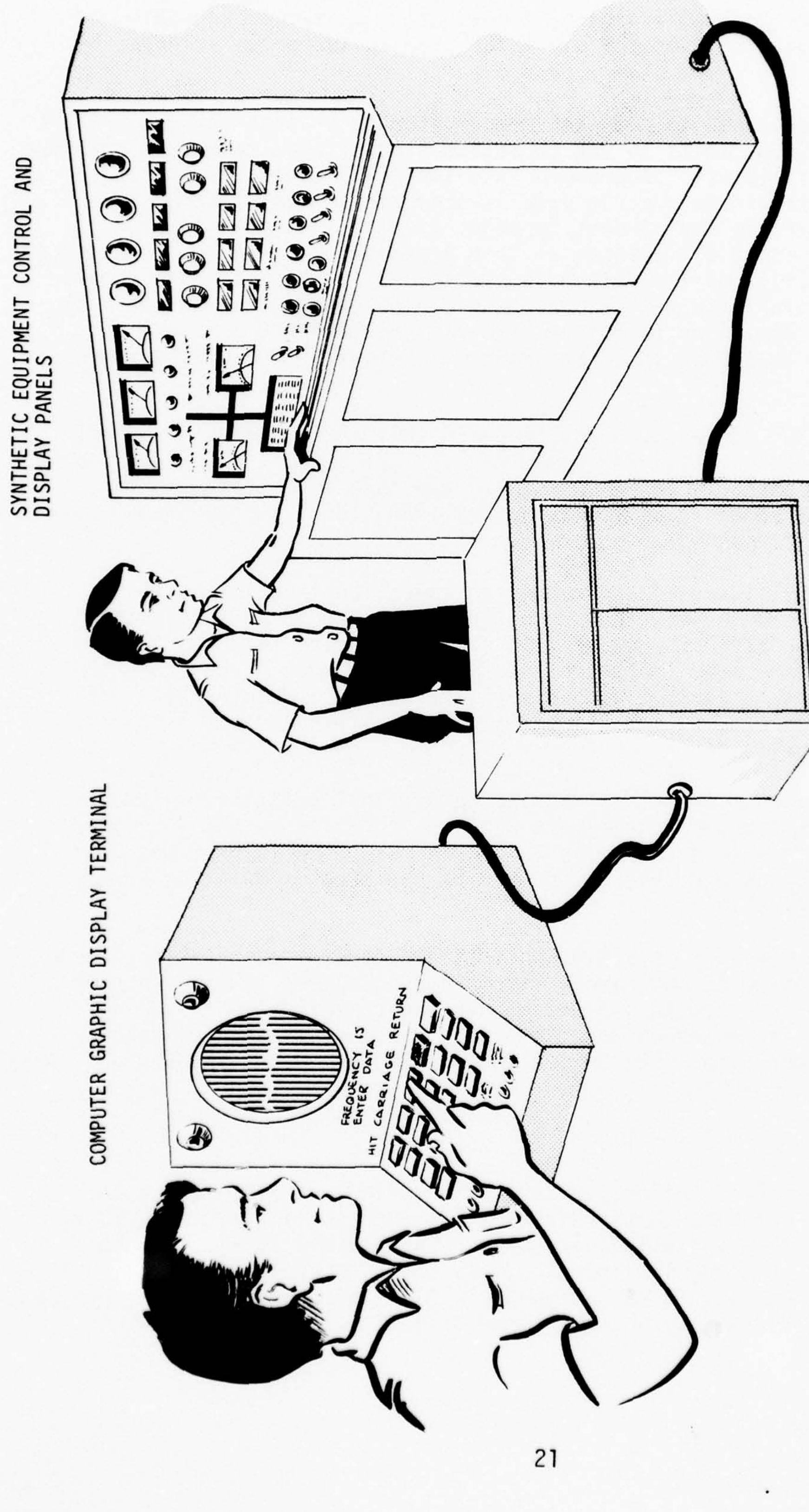


Figure 4. Maintenance Training Data Generation via Computer Simulation Program

tests or measurements, prestored data from computer memory creates a display of the test or measurement results. The display may be via computer graphic CRT systems, simulated meters, indicator lamps, etc., as are appropriate for the data display requirements or the simulator display technique selected by the EEMTD developer.

An alternative approach to computer memory storage of test and measurement data, long considered but still in the formative stages, uses math models of the operational equipment circuits programmed into the EEMTD computer. During a training exercise, circuit parametric data is computed in real time or near real time and displayed to the student by means similar to those shown in figure 4. The fundamental differences in this approach over the two discussed above are the flexibility of the data base and the ability to generate dynamic data. In effect, an infinitely rich data base can be generated with the math modeling technique. The other techniques are limited to those a priori sets of data selected for training, thus requiring more highly structured maintenance training scenarios.

CRITIQUE OF THE CURRENT STATUS OF COMPUTER-BASED EEMTD APPLICATIONS PROGRAMS. The instructional concepts utilizing computers for CMI and CAI are well established. Application of these concepts in EEMTD is more the rule than the exception. Appendix B provides a representative listing of operational CAI programs, many of which contain CMI components.

Of the previously discussed approaches to operational equipment/test equipment functional simulation, the photographic storage technique is in common use in existing EEMTDs. However, it should be noted that this technique is not truly a computer-based (software) simulation but more a technique that employs the computer as a control mechanism. The future characteristics of these control programs will be influenced largely by advances in the state-of-the-art in audio/visual media.

The EEMTD software technique of storing operational and test equipment functional data in static digital formats within a computer is the only true software simulation technique currently in general use. Decisions regarding the use of this technique are influenced more by choice of simulation approach than by engineering capability.

The use of math modeling in EEMTD applications to create operational and test equipment environmental data is in its infancy compared to the state of the art in math modeling used in synthetic operator training devices. Only one application of this technique was identified. It is the Sophisticated Instructional Environment (SOPHIE) Device (Brown, Burton, Bell, and Bobrow, 1974) and is discussed subsequently.

COMPUTER-BASED EEMTD

The remainder of this section provides descriptions of computer-based EEMTD configurations and discusses their capabilities and limitations. There are a number of ways in which existing computer-based EEMTD configurations can be classified. A consensus within the Navy training community is to segregate these devices into three categories: (1) flat-panel system simulators, (2) computer graphic terminals, and (3) three-dimensional simulators.

FLAT-PANEL SYSTEM SIMULATORS. The flat-panel devices, as the name implies, depict elements of real equipment pictorially or schematically in two dimensions. The more sophisticated of these trainers contain actual controls (knobs and switches, etc.) and displays (indicators, lights, dials, etc.) appropriately located on the two-dimensional panels. These controls and displays are "active" through interconnection with a computer. Thus they function as in the actual equipment. Some flat-panel devices also incorporate visual systems which provide photographs of actual equipment, checklists, instructions, and other graphic materials. Such devices do provide for some realistic "hands-on" training by allowing students to manipulate the knobs, switches, and other controls. Flat-panel devices are typically used to provide organizational level preventive and corrective maintenance training. Organizational level repair is generally limited to front panel "black box" checks to locate, remove, and replace line replaceable units.

COMPUTER GRAPHICS TERMINAL SIMULATORS. Computer graphics terminals are increasing in use as maintenance trainers. The characteristics of information (alphanumeric, line-drawing, or pictorial) displayed and the type of human interface controls employed (keyboard, light-pen, or touch panel) can vary widely in these devices. A major advantage of these devices is flexibility through computer programming/reprogramming. That is, unlike flat-panel EEMTDs, where both computer programs and flat panel hardware changes are required when new equipments are simulated, a single type computer-graphic terminal can be used to simulate a variety of electronic equipment and electronic testing devices. While computer-graphic devices offer great flexibility, they do incur a considerable limitation in physical fidelity for most maintenance tasks. Thus they are best suited to instructing highly cognitive type tasks.

THREE-DIMENSIONAL EQUIPMENT SIMULATORS. This category of device can be viewed as "active" mock-ups of the actual electronic systems and testing equipment. Existing computer-based three-dimensional training devices simulate portions of operational equipment; i.e., a complete external/internal functional simulation of operational equipment has not been accomplished. These devices provide training on representative samples of maintenance tasks required to maintain the simulated equipment components. Their three-dimensional construction facilitates more extensive hands-on training than is possible with most other maintenance training devices.

AN EEMTD POSSESSING DYNAMIC SIMULATION PROGRAMS. One EEMTD, known as SOPHIE (Brown, et al., 1974), has many interesting attributes. SOPHIE utilizes software math modeling to generate electronic equipment functional data in real time during training exercises. Technically, SOPHIE would be classified as a computer graphics terminal; however, it is being presented as a special EEMTD due to the characteristics of the simulation application program.

The SOPHIE math model(s) simulation and CAI architecture provide a rich set of alternative strategies which a student may follow. The student may develop a hypothesis, test the hypothesis, and receive feedback from the training device regarding the accuracy of the hypothesis. In essence, SOPHIE

contains a form of artificial intelligence. This capability is a powerful aid in teaching complex skills (an important requirement for proficient electronic equipment maintenance). The EEMTDs discussed previously provide highly structured training exercises involving simple operations where student choice in developing and pursuing alternate preventive and corrective maintenance strategies is limited to the options programmed in the device.

SOPHIE's unique capabilities are derived from a modified version of a software program used in the design and development of operational electronic equipment. This program is called ISPICE (see references in bibliography). A detailed discussion of circuit design computer programs follows in section III. Appendix C contains additional information on SOPHIE.

SECTION III

NEW SOURCES OF COMPUTER-BASED EEMTD SOFTWARE

AN OVERVIEW OF AUTOMATED DESIGN SOFTWARE

Computer programs have reached a prominent position in the automated design, development and manufacture of electronics equipment. Spurred by requirements in microelectronics, computers are being designed to perform tasks that are either impractical, dangerous or impossible by traditional manual man/machine techniques. Computer applications programs in electronic equipment manufacturing can be placed into three categories:

- Computer-Aided Design (CAD)--the software programs that are utilized in electronic systems circuit design, development, and testing.

- Design Automation (DA)--software programs which are used to translate a design to hardware layout. An example of DA is the automatic design of the routing of connecting paths on a printed circuit board.

- Computer-Aided Manufacturing (CAM)--those software programs which generate outputs directly used in the fabrication of hardware. An example of CAM is an automated wire-wrap machine.

Figure 5 shows a typical design, development, and manufacturing cycle for modern electronics equipment and the processes in the cycle where CAD, DA, and CAM programs are used. In addition, the percent automation for each process is identified along with the points where human interface is required in the complete cycle.

Automated design of electronics equipment is a mature technology. Table 2 lists computer-aided design software development data for 21 electronic and aerospace companies. Seven of the 21 companies surveyed provided cost data. These seven invested a total of over $30 million in CAD, DA, and CAM programs. Of the total companies surveyed, 17 provided data on time invested in program development. These 17 companies combined have a total of 132 years in computer-aided program development. As of January 1978, over 1,100 automated design programs are in industrial use with a tenfold increase expected in 5 years.

RELEVANCE OF AUTOMATED DESIGN PROGRAMS TO EEMTD. Automated design software programs produce data applicable to EEMTD. Both DA and CAM programs generate schematic and line drawing data for operational electronic equipment. CAD programs which simulate the operation of electronic equipment circuits are capable of computing initial circuit conditions, transient conditions and/or steady-state conditions. The conditions can be established for normal circuit configurations, simple and catastrophic component failure simulation, power turn-on/turn-off effects, and circuit/system operation for an almost infinite

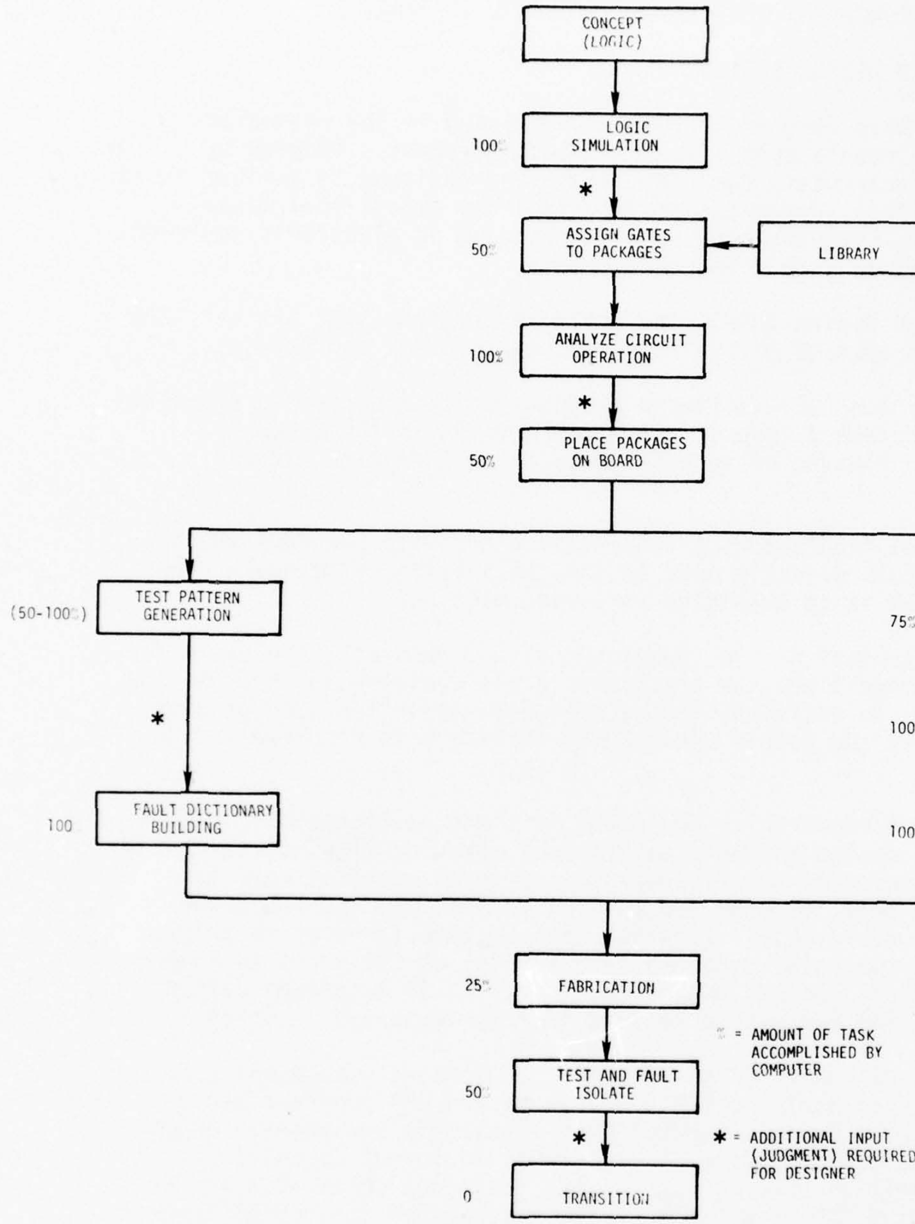


Figure 5. Typical Work Flow Using Design Automation for Digital Electronics (Reproduced from Owens, Ray, Harper, 1975)

TABLE 2. COMPUTER-AIDED DESIGN PROGRAM DEVELOPMENT AND EXPENDITURE DATA FOR ELECTRONIC AND AEROSPACE COMPANIES

Company	Technologies Aided	CAD SYS Develop Time (Years)	Sunk Cost ($M)	Current Expendit Rate ($M/YR)
1	PHL	7	-	1
2	PHL	9	10	0.5
3	PHL	10	-	1
4	PL	10	2.5	-
5	PL	-	-	0.5
6	L	4	1	0.1
7	P	13	-	-
8	PL	12	-	-
9	PHL	7	-	-
10	P	15	6	-
11	PHL	5	-	-
12	P	-	-	-
13	PHL	10	10	1
14	PL	-	-	-
15	L	4	-	0.1
16	PHL	10	-	-
17	P	4	-	1
18	P	7	0.2	-
19	P	-	-	0.08
20	PL	4	-	-
21	L	0.5	0.25	0.5

P = Printed Circuit/Wire-Wrap
H = Hybrid Circuit
L = Large Scale Integration

(Source: Owens, Ray, Harper, 1975)

variety of circuit component value variations. A number of CAD programs, for example, SUPER SCEPTRE (Bowers, O'Reilly, and Shaw, 1975) and CIRCUS (Dembart and Milliman, 1976), can handle almost any conceivable system description. The data are generated in real time by a math model containing circuit topology and component values. Outputs from DA, CAM, and CAD programs can be presented in numerous formats via hardcopy or computer graphic displays.

A CAD Program With Inherent Electronic Maintenance Training Capabilities. Tests and measurements are as important to electronics design engineers as they are to maintenance technicians. As depicted in figure 6, the design engineer uses tests and measurements of circuit/system performance to determine that design goals have been reached. Though for a different purpose, many of the engineer's tests and measurements are the same ones a technician will make to perform system maintenance. The Hewlett-Packard Laboratories, Palo Alto, California, recognized the value in providing design engineers with circuit parametric data in familiar test equipment display formats and developed CAD software possessing such capabilities. Several things are significant about the Hewlett-Packard Computer-Aided Design (HPCAD) program. HPCAD was designed to run on a minicomputer. (Most of the CAD programs listed in appendix D require large expensive computer systems to run the programs.) HPCAD contains models of an oscilloscope, a waveform analyzer, a frequency counter, a Harmonic analyzer, impedance meters, and signal generators as integral components of the program. When circuit/system parametric data are measured, using the simulated test equipment, the data are displayed in hardcopy or on a computer graphic terminal as they would appear on the actual test equipment being simulated, and in real time as the circuit operates. Therefore, those circuit parameters that are time varying are appropriately displayed. In addition, changes to circuit conditions; e.g., input signals, component values, and/or tests configurations can be made in real time. Additional data on HPCAD are contained in appendix E. In terms of application, there appears to be a high correlation between the adaptations made in the HPCAD and the applications of the ISPICE CAD program in the SOPHIE EEMTD.

ADAPTATION OF AUTOMATED DESIGN SOFTWARE FOR MAINTENANCE TRAINING. The use of CAD programs in the SOPHIE EEMTD and in the mechanization of the HPCAD software clearly demonstrates the value of automated design programs in training applications. It is surprising to note that developers and users of automated design programs did not fully appreciate the training applications. Their awareness, however, was heightened during discussions with TAEG personnel. For example, one corporation suggested that the training application of automated design programs should be the final logical extension of the automated equipment production process; i.e., design, develop, test, manufacture, train. The members of the automated design community were quick to point out that the use of CAD, DA, and CAM software in training applications may not be a straightforward one-to-one translation. Some of the negative factors cited were:

- the majority of the programs require large expensive computers to permit operation

- many circuit problems require long solution time, making real time problem solutions questionable

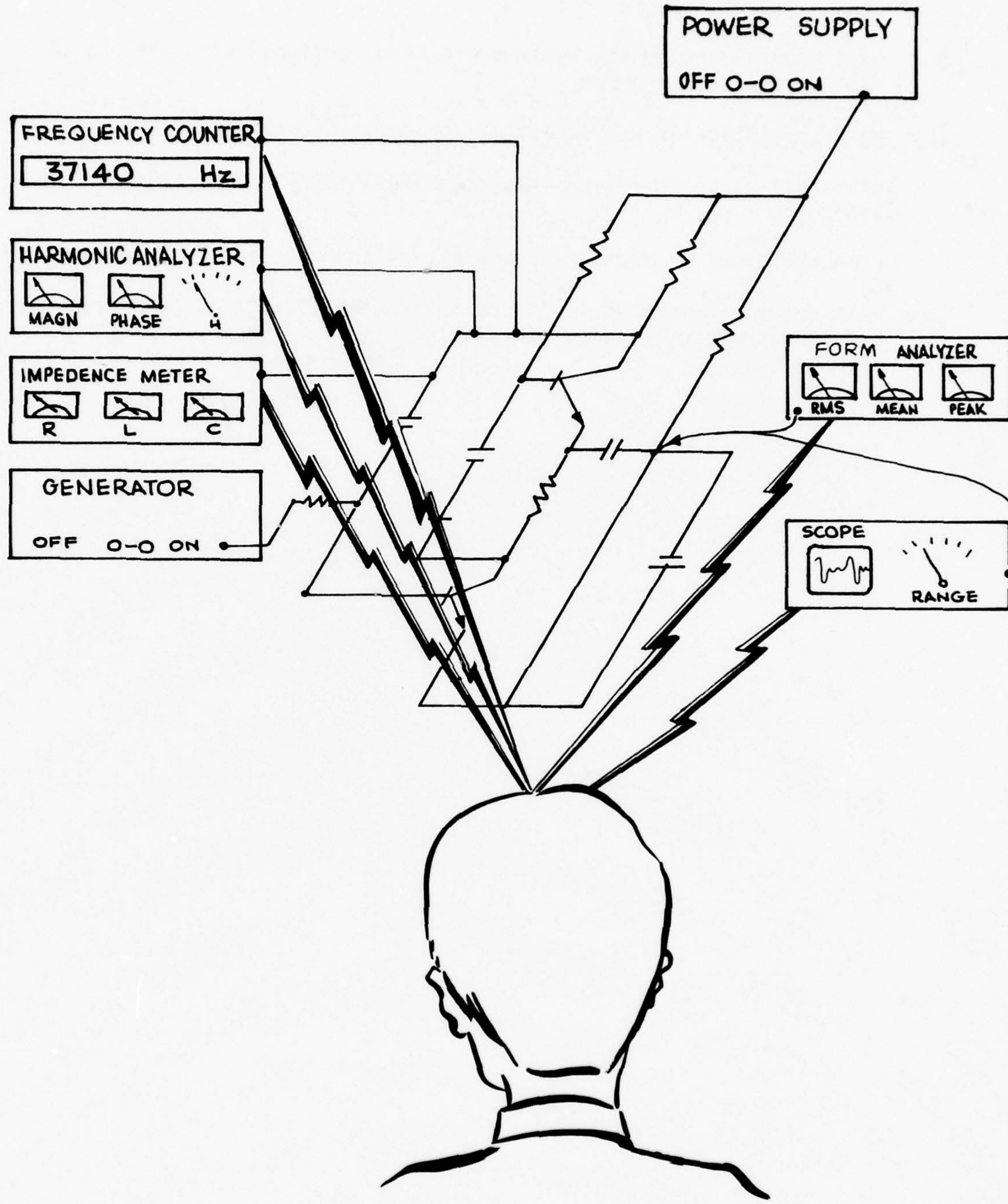


Figure 6. An Illustration of Circuit Design Analysis by an Engineer Using Test and Measurements

(SOURCE: FAZARINC, 1973)

- accurate circuit models are difficult to develop.

On the plus side, the following is cited:

- most modern electronics systems are being designed with the aid of automatic design programs
- more sophisticated design automation programs are evolving
- libraries of standardized accurate circuit models are rapidly expanding
- computer power is increasing while size and cost are decreasing
- with increasing awareness of training needs, design automation programs can be made more training compatible.

SECTION IV

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

The following conclusions are suggested from the study findings:

- Not all computer-based EEMTDs contain programs that generate emulations of static and dynamic electronic equipment front-panel and internal circuit operational characteristics.

- EEMTDs that contain computers can effectively use CMI and CAI programs for record keeping, peripheral equipment control, and automation of instruction.

- The most widely used computer-based EEMTDs provide equipment front-panel simulation. This type of simulation for maintenance training purposes appears to have been influenced by the existence of applicable <u>operator</u> training device simulation technology.

- Software simulation of equipment internal circuit dynamics for use in hands-on maintenance training is in its infancy. This situation appears to result from the difficulty in developing simulation models to handle the large number of variables involved in generating dynamic and static circuit parametric data.

- A large and rapidly expanding technology exists in the field of computer-aided design and manufacturing of electronic equipment. This technology has potential application in a number of maintenance training areas:

    - Computer-aided design circuit simulation programs could significantly advance the state-of-the-art in circuit level hands-on training capabilities of computer-based maintenance training devices. In addition, the programs are also applicable to front-panel simulation.

    - Computer-aided design analysis and manufacturing programs offer automated data bases for schematics, assembly layout, card/component layout and technical data that could support EEMTD data requirements and non-EEMTD training material data requirements.

- Computer-aided design software programs and system data are utilized at the earliest points in operational equipment development. The early availability of these programs and data offers the potential of having training programs (including EEMTD) available at the introduction of the operational equipment. This is significant since operational equipment design/development and production cycles are compressed in time when computer-aided design is used. Training

system development cycles will require commensurate time compressions to provide the requisite support for the equipment. Figure 7 illustrates how design automation programs could support concurrent development of operational equipment and maintenance training system components.

- A transfer of computer-aided design technology to training device technology will require increased interactive efforts between training researchers and personnel knowledgeable in the field of automated design. At present, there is a lack of communication between the training communities and the computer-aided design communities.

RECOMMENDATIONS

It is recommended that CNO sponsor an RDT&E program to initiate the transfer of computer-aided design technology to military electronic equipment maintenance training. The initial step proposed for establishing this program is a series of working group sessions composed of selected personnel from tri-service training and experts in the field of computer-aided design technology. The initial working group meetings should be convened for the purposes identified below. It is recommended that the TAEG assist the CNO in the identification of attendees.

Working Group Meeting No. 1. This meeting should present the Department of Defense (DOD) needs in electronic equipment maintenance training. The meeting should result in identifying specific issues for members of the design automation community to investigate.

Working Group Meeting No. 2. This meeting should examine the results of design automation community investigations of the critical areas identified during meeting No. 1. The results of this meeting should be the formulation of community initiatives on potential uses of design automation software in training.

Working Group Meeting No. 3. This meeting should enable the design automation community to present recommendations on potential uses of design automation software in training to the DOD representatives. It should result in the formulation of a design automation/training community program plan of action for implementing design automation software in training in areas of highest potential payoff.

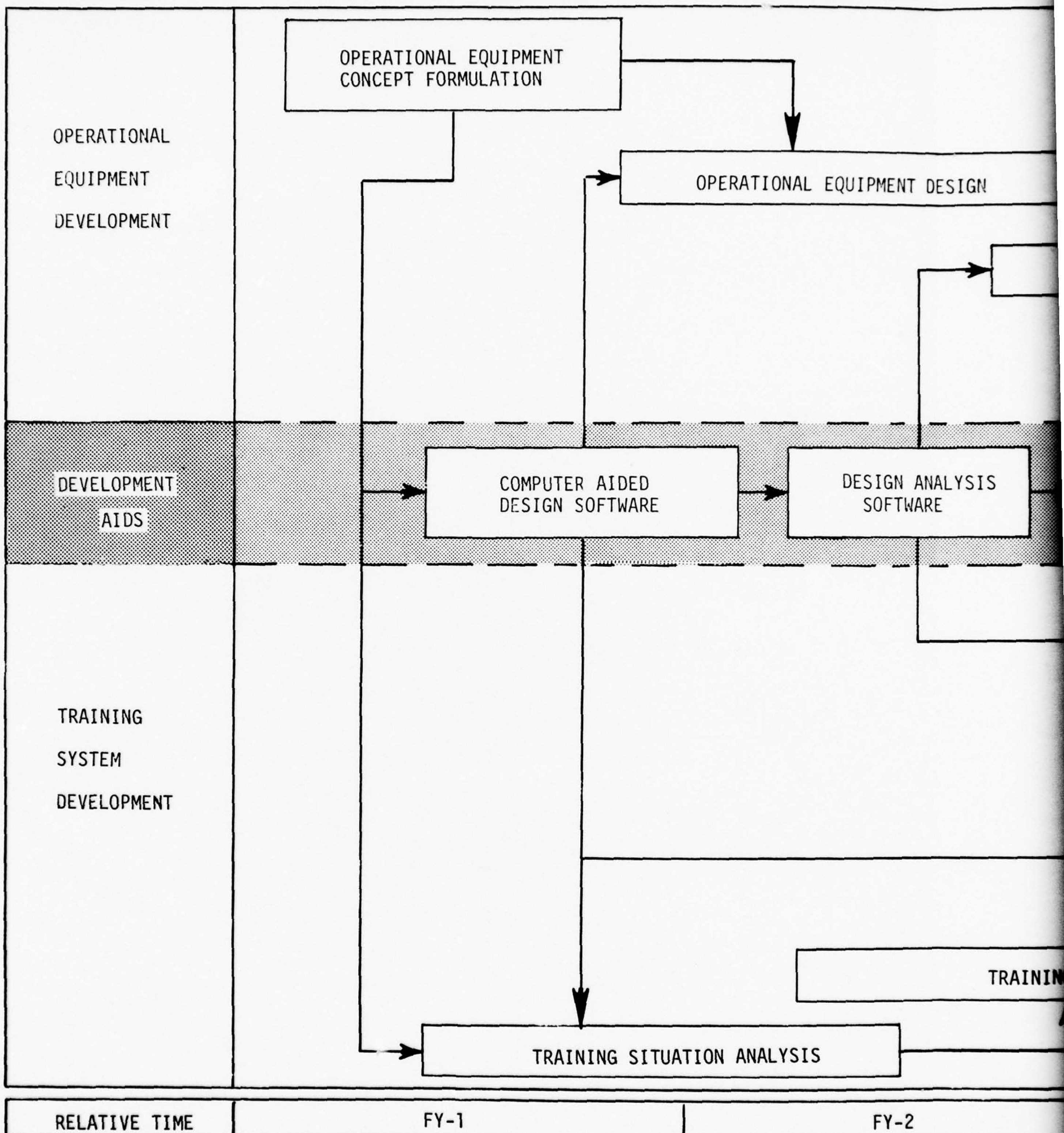
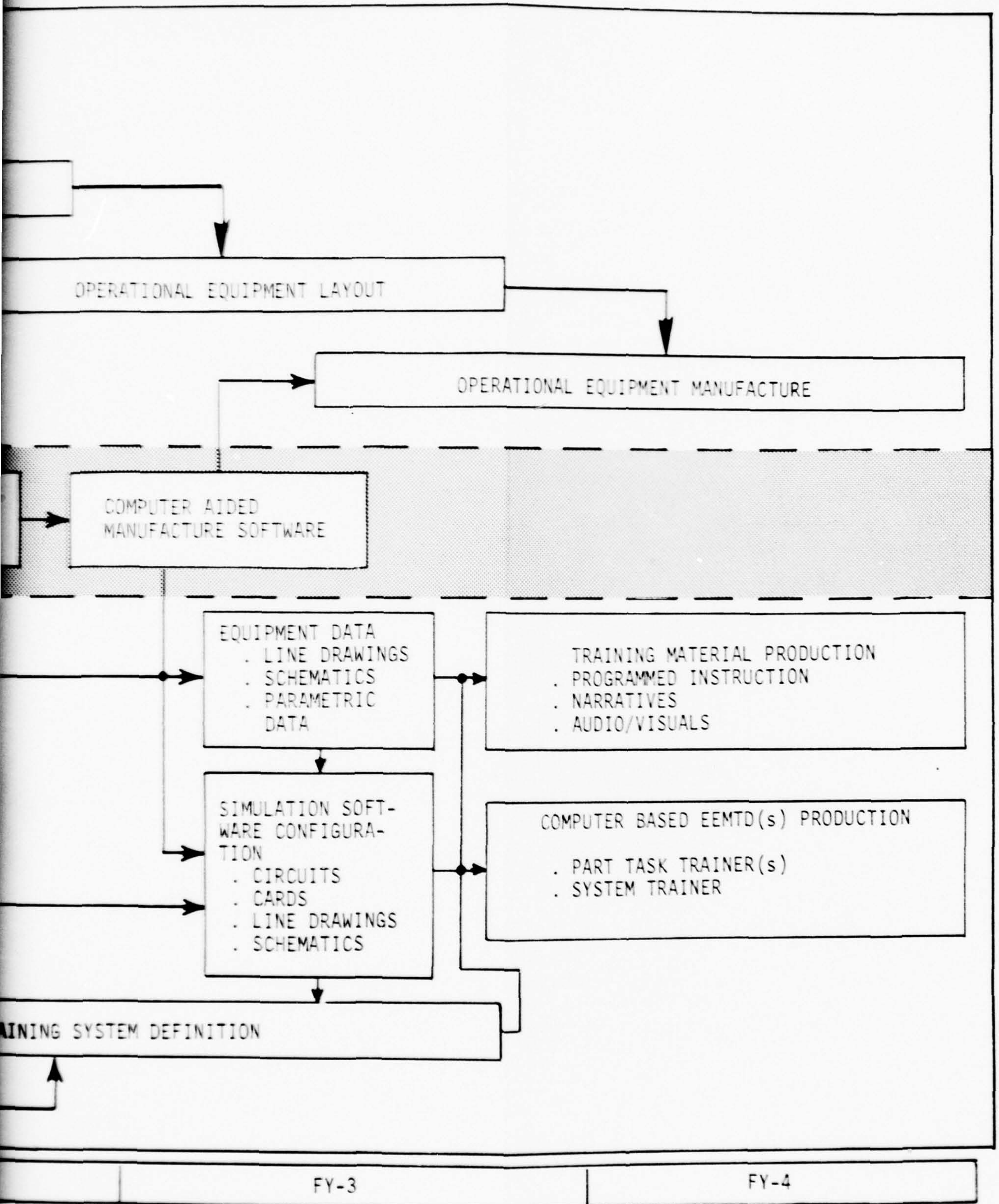


Figure 7. Design Automation Software Ap
of Operational and Training E



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APPENDIX A

DATA SOURCES

DATA GATHERING TRIPS

COMPANY/GOVERNMENT ACTIVITY VISITED	PURPOSE
Naval Training Equipment Center Orlando, Florida	Discussions on state-of-the-art Electronic Equipment Maintenance Training Simulators
Educational Computer Corporation Orlando, Florida	Trainer manufacturer
Harris Corporation Melbourne, Florida	National CSS, Inc. ISPICE computer-aided circuit design program user
Air Force Avionics Laboratory (AFAL), Wright-Patterson Air Force Base, Ohio	Computer-aided design user. Produced 1975 report assessing state-of-the-art in computer-aided design
Super Sceptre Course Wright-Patterson Air Force Base, Ohio Contact: Dr. J. C. Bowers	Obtain working knowledge of a computer-aided circuit design program and become familiar with its advantages and disadvantages
Boeing Computer Services, Inc. Seattle, Washington	Discuss computer-aided design and manufacturing applications
Hewlett-Packard Laboratories Palo Alto, California Contact: Dr. Zvonko Fazarinc	Discuss applications of "designer-oriented" computer-aided design utilizing minicomputers
University of Southern California Behavioral Technology Laboratory (BTL) Los Angeles, California Contact: Dr. J. W. Rigney	Discuss TASKTEACH and other maintenance simulation efforts at BTL.
Naval Air Station, North Island San Diego, California	Attend LOGIC Model Test Set demonstration presented by U.S. Army Air Mobility Research and Development Laboratory, Ames Research Center, Moffett Field, California
Ling-Tempco-Vought Dallas, Texas	Discuss simulation concepts for maintenance training
Texas Instrument Dallas, Texas	Discuss computer-aided design and manufacturing applications
University of Florida Gainesville, Florida Contact: Dr. Stephen Director	Discuss computer-aided design and manufacturing applications

DATA SEARCHES

DEFENSE DOCUMENTATION CENTER (DD1498 Forms) WORK UNIT SUMMARIES--MAINTENANCE TRAINERS, 311 PAGES

DEFENSE LOGISTICS STUDIES INFORMATION EXCHANGE (DLSIE)--COMPUTER AIDED DESIGN

DEFENSE LOGISTICS STUDIES INFORMATION EXCHANGE (DLSIE)--MAINTENANCE TRAINING

INDEPENDENT RESEARCH AND DEVELOPMENT REPORTS--COMPUTER AIDED DESIGN, 77 PAGES

NASA LITERATURE SEARCH (No. 34155)--COMPUTER AIDED DESIGN OF ELECTRONIC CIRCUITS, 108 PAGES

NASA LITERATURE SEARCH (No. 34155) PART II--(LIMITED DISTRIBUTION REFERENCES) COMPUTER AIDED DESIGN OF ELECTRONIC CIRCUITS, 1 PAGE

NASA LITERATURE SEARCH (No. 34125)--MAINTENANCE TRAINERS, 17 PAGES

NASA LITERATURE SEARCH (No. 34125) PART II--(LIMITED DISTRIBUTION REFERENCES) MAINTENANCE TRAINERS

RESEARCH AND DEVELOPMENT PLANNING SUMMARY (DD FORMS 1634)--MAINTENANCE TRAINING, 18 PAGES

APPENDIX B

COMPUTER ASSISTED INSTRUCTION (CAI) SYSTEMS

COMPUTER ASSISTED INSTRUCTION (CAI) SYSTEMS

CAI ACRONYM	DESCRIPTION
APL	A Programming Language. A scientific-mathematical language first developed by IBM. It is an interactive language with several facilities for CAI. Orange Coast and Golden West Junior Colleges in Orange County, California, have used the language extensively for CAI.
CD/TS	Computer-Directed Training Subsystem. A CAI system developed by Systems Development Corporation.
CHIMP	CAI system developed by Institute for Molecular Physics, University of Maryland.
CLIC	Conversational Language for Instructional Computing. A multipurpose CAI language.
COPI	Computer-Oriented Programmed Instruction. A system written and marketed by UNIVAC. This system is being used by the Marine Corps at Twentynine Palms, California.
COURSEWRITER	The first author-language for CAI. It was developed by IBM and is the most used CAI language in the world. The system operates all through the United States and Europe. A COURSEWRITER system has been in use for several years at Fort Monmouth.
ELIZA	A language developed by MIT. The language has interesting capabilities for simulated dialogue.
FOIL	File Oriented Interpretive Language. Developed at the Center for Research on Learning and Teaching, University of Michigan.
LOGO, MENTOR, SCHOLAR, SIMON, STRINGCOMP	These five systems are all special experimental CAI languages developed at Bolt Beranek and Newman. All are written in various special-purpose languages.
LYRIC	Language for Your Remote Instruction by Computer. A fully conversational CAI language.
PCDP	Physics Computer Development Project. An excellent language specifically suited to Physics and other hard sciences with excellent use of graphics.
PIL	Pittsburg Interpretive Language. A CAI system written in assembly language for the PDP-10.
PLANIT	Programming Language for Interactive Teaching. PLANIT is generally recognized as the most complete and versatile of the CAI author languages.

COMPUTER ASSISTED INSTRUCTION (CAI) SYSTEMS (continued)

CAI ACRONYM	DESCRIPTION
PLATO	Programmed Logic for Automatic Teaching Operation. This system is now in its fourth generation. Its present language is called TUTOR. PLATO consists of several special pieces of hardware, among them the PLATO IV Plasma Display Terminal.
RASCAL	Rudimentary Adaptive System for Computer-Aided Language. Produced as part of a Master's thesis by Lt. John Christopher Stewart, USN, for a Master of Science in Computer Science from the Naval Postgraduate School, Monterey, California. The system is written in PL/1.
SCHOLAR-TEACH	An elementary CAI system written in machine language for the DEC-System 10.
TICCIT	Timed-Shared, Interactive, Computer-Controlled Information Television. TICCIT is a specialized CAI system using mini-computers, cable television, and color television with keyboards as input/output devices.

APPENDIX C

APPLICATIONS OF ARTIFICIAL INTELLIGENCE TECHNIQUES IN MAINTENANCE TRAINING

APPLICATIONS OF ARTIFICIAL INTELLIGENCE TECHNIQUES IN MAINTENANCE TRAINING

JOHN SEELY BROWN and ROBERT J. BOBROW
Bolt Beranek and Newman Inc.

Introduction

Recent trends in artificial intelligence (AI) techniques and computer technology show promise of supporting a qualitatively new kind of maintenance training which can provide high quality instruction at the training site and can then integrate on-site job performance aids (e.g. computer-based consultation) [Hart 75] with more specialized on-site tutoring. By integrating job performance aids with tutoring systems the trainee can get into the field faster and "learn by doing" (and while doing) without overly taxing the experts at the job sites with naive questions and costly mistakes. The viability of integrating job performance aids with tutoring systems depends in part on the ability to create intelligent computer-based systems. These systems must have sufficient built-in knowledge and problem-solving ability that they can, on their own, answer questions, evaluate hypotheses, provide suggestions as to which diagnostic procedures to employ next, and provide helpful supervision while the trainee carries out complex tasks. If the computer system can not only solve problems and make intelligent decisions as to how to perform a maintenance task, but can also justify or explain its own decisions, it can form the critical ingredient of an intelligent training system as well as of an intelligent job performance aid.

In this paper we describe some of the ways in which artificial intelligence techniques might be used to provide training and performance aids for maintenance. These speculations are based in part on SOPHIE*, a kernel instructional system which provides a first step in creating training systems which manifest active intelligence, and in part on the following three trends which we have observed:

i) the cost of computation is becoming dramatically cheaper, and advances in computer technology and artificial intelligence are making a whole new range of training and maintenance aids both technically possible and economically feasible

ii) the complexity of the maintenance skills to be taught and performed is increasing because of the increased sophistication of equipment and operational procedures

iii) the cost of the human-mediated aspects of training and maintenance is constantly increasing.

Computer systems which do not have the abilities to understand new problems and questions arising during maintenance tasks can function as only limited performance aids, and can provide training only in highly structured and restricted tasks. For example, a training system which cannot itself generate solutions to problems arising during training tasks, can only aid the trainee by presenting "canned solutions" provided by an author of the system. This means that the training system can not capitalize on unanticipated problematic situations that the trainee encounters while performing his task in order to further his understanding.

Similarly, a training system which does not itself understand the purpose and interaction of various actions, measurements and tests involved in a maintenance procedure, can only criticize and correct a trainee's procedure to the extent that

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* This system is described in the second section of this paper. Some portions of that section are revised versions of prior papers.

(Source: King and Duva (Eds.), 1975)

the errors involved have been explicitly described by the system author and proper "canned criticism" stored. Such a system may not pinpoint the trainee's mistake leading to a difficulty especially if his error does not cause observable problems until much later in the maintenance procedure.

This leads us to believe that artificial intelligence can have a major impact on the training and performance of maintenance personnel by providing the problem-solving and reasoning capabilities needed to produce:

i) sophisticated training systems which understand the procedures and associated problems involved in difficult maintenance operations. Such systems could provide instruction, evaluation and remediation in the performance of maintenance tasks, with explanations and instructions adapted to the trainee's current state of knowledge.

ii) performance aids for maintenance personnel. Such computer-based consultants could conveniently and effectively provide information which can currently be obtained only by consultation with experts or study of general maintenance documentation. These consultants can solve problems arising during maintenance tasks, provide instruction as to optimal maintenance or debugging strategies, and can evaluate alternative courses of action based on current conditions.

iii) aids for the author of training and performance programs. Intelligent systems that understand maintenance problems and the operation of devices to be maintained can facilitate production of training and performance aids for new equipment and new training or maintenance procedures.

We recognize that creating intelligent systems that have all the above properties is a major research challenge!

Training Considerations

The critical characteristic of maintenance training is that such training must impart complex skills to the trainee, not simply knowledge of a collection of facts nor the ability to perform simple repetitive operations. Such skills involve the integration of both factual information and operational capabilities into a unified goal-oriented procedure, defined by the properties of the final state to be reached (e.g. a properly functioning device) rather than by any simple arrangement of tests and operations. Some important classes of capabilities which must be coordinated and integrated are:

i) information gathering (how to take a measurement or make a test)

ii) adjustment or calibration (how to align a receiver)

iii) decision making (what is wrong, what is the best test to perform, what is the best repair)

iv) problem solving (how do I remove this housing without affecting the alignment of that sub-assembly), and

v) reasoning (what will happen if I remove this spring to get access to that bolt).

A training environment must not only teach trainees these individual capabilities, but help them to organize these capabilities into procedures for dealing with the expected range of maintenance problems.

In order to effectively achieve such training, an intelligent instructional system must have a model for the procedures embodying the

desired skills. This model must be usable in several ways, including:

i) descriptive explanation and question answering about the maintenance skill and its component capabilities

ii) active problem solving - show the student how to perform a particular task - not just a fixed set of examples, but in response to such student questions as "I can do everything but figure out how to replace housing A while sub-assembly B is removed, in order to test out the functioning of the speed regulator - what do I do?"

iii) monitoring of trainee during task performance in order to point out actual errors or possible future problems due to neglect of critical tests or actions (e.g. "You forgot to check the tightness of the set screws before replacing the housing, and the rotor may slip when you are testing the speed regulator, giving erroneous readings.")

In complex skills there will always be alternative techniques involving variation in details and ordering, as well as possibly differences in overall structure. In order to ensure that the trainee has learned the skill in a manner which will apply to a wide range of problem situations, and not merely to the set of test exercises given during training, the instructional system must be able to evaluate and critique the structure and function of the trainee's procedure, It does not suffice to simply evaluate its results in a few test cases! To effectively show why certain decisions that seem to work in some cases are not generally valid, the instructional system must be <u>able to generate test cases</u> for which the inadequate rule produces results that the trainee can see are wrong.

A particularly useful way for a trainee to master the skills needed for maintenance is to qualitatively understand the structure and operation of the device to be maintained. To facilitate this understanding, the program must itself understand the design and functioning of the device. This will provide the basis for training programs that can <u>interact</u> with the trainee, as well as present material and evaluate results. Such a program will be able to answer questions about the operation of equipment under various conditions, and about the ways in which the equipment can fail and produce some observable set of symptoms. The answers to such questions can help the trainee develop sound intuition for the operation of the equipment and its possible malfunctions. Such programs will also be able to answer questions as to "why" a particular piece of equipment is designed in a particular way, what purpose is served by various modules. By combining such a question-answerer with another program that observes a trainee's progress in solving a problem, it is possible to incorporate general teaching about the properties of the equipment into the process of solving specific problems, thereby directly linking the general knowledge to the problem solving process. By combining such a capability with models for the current competence level of the trainee, the system can give answers in terms of concepts understandable to the trainee, and at a level of detail suitable to the purpose for which the question is asked.

As mentioned in the introduction, many of the capabilities described above for the instructional system are essentially what one might want in performance aids. This is not surprising since A GOOD TEACHER MUST KNOW HOW TO <u>PERFORM</u> THE TASKS HE ASSIGNS HIS STUDENTS, AS WELL AS KNOWING HOW TO HELP THEM WHEN THEY ARE HAVING DIFFICULTIES. The planning and problem solving techniques developed to provide instructions and warnings for trainees can supply maintenance personnel with a performance aid. Such techniques can be used to determine the best way to meet a certain goal (dis-assembling a component, replacing a part) given the context determined by previous actions (the physical state of the mechanism, what portions have been removed or dis-assembled) and available resources

(tools, personnel, time). The techniques can also be used to warn of dangers or errors likely in performing some action in the current context.

As in the training process, a critical issue in the design of a performance aid is its ability to communicate with the personnel (in a natural way), to provide procedural information on how to remove, dis-assemble, adjust, align, calibrate or simply take measurements. These instructions must be neither too terse, nor too voluminous. Thus the program must make use of:

i) a model of the user to tell what he knows and what operations he has previously had difficulty performing

ii) feedback from the user, and problem solving capabilities to help the user when there is difficulty in following instructions (due to unusual states of the device, or to misunderstanding or error by the user).

The job of preparing training material and maintenance aids (handbooks) can be simplified by the development of appropriate intelligent programs. For example, a general "electronics maintenance system" (for more limited purposes, a "VHF transceiver system") could be built with knowledge that would permit it to read circuit diagrams and design descriptions for a new piece of equipment. In conjunction with a human expert, such a system could help develop training programs for the new equipment, or maintenance and debugging strategies to be incorporated in performance and training aids.

Section II*

A SOPHisticated Instructional Environment -- SOPHIE

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*The research project described in this section was supported in part by the Air Force Human Resources Laboratory, Technical Training and ARPA-HRRO.

In this section we describe the techniques used to instill active intelligence into a prototype instructional system (named SOPHIE) for use in improving a trainee's qualitative understanding of the logical structure of, and troubleshooting techniques for, complex feedback systems.

SOPHIE was designed to fulfill two main objectives. The first was to demonstrate the feasibility of using AI techniques to construct an expert or intelligent training system which, on its own, could reason, answer questions, evaluate a trainee's hypothesis, critique his behavior and in general carry on an intelligent tutorial dialogue. That is, a system which can not only regurgitate factual information but can also use its knowledge to carry out logical tasks (which is also a first step toward an intelligent performance aid). The second was to explore some qualitatively new kinds of training scenarios which utilize instructional strategies that exploit the significantly increased computational capabilities provided by advances in hardware technology. Such scenarios were impossible within the traditional CAI framework because they required the reasoning capabilities comparable to that of human tutor operating in a one-to-one relationship with a trainee.

Basic Scenario

In the basic scenario, SOPHIE acts as an electronics lab instructor who helps the trainee transform his classroom knowledge of electronics into an experiential, intuitive knowledge of its meaning and application. SOPHIE does this by interacting with the trainee while he is debugging a malfunctioning piece of equipment.* The trainee can perform any sequence of measurements, ask either specific questions about the implications of these measurements or more general hypothetical questions,

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*Although throughout this paper the domain of knowledge under consideration is electronics, the reasoning and linguistic paradigms underlying SOPHIE are applicable to many domains outside of electronics.

even asking for advice about what to consider next, given what he has discovered thus far. At any time SOPHIE may encourage the trainee to make a guess as to what he thinks might be wrong given the measurements he has made thus far. If he does, SOPHIE will evaluate his hypothesis by taking into consideration all the information he should have been able to derive from his current set of measurements. If any of this information is logically contradicted by the hypothesis, SOPHIE identifies and explains these contradictions. Likewise SOPHIE can judge the merits of any particular measurement with respect to the prior sequence of measurements he has made. For example his new measurement may be logically redundant in the sense that no new information can possibly be derived from it (this may be extremely difficult to determine). SOPHIE can also decide if this measurement performs a reasonable split of the hypothesis space of possible faults which have not yet been ruled out by prior measurements.

It should be noted that the above scenario requires SOPHIE to perform a variety of logical tasks (i.e. hypothesis formation, and evaluation, redundancy checking, (answering questions which may involve logical hypotheticals) each one of which requires a substantial amount of deep logical inferencing. Few, if any, of these tasks could be achieved by using, for example, pre-stored decision trees - since the exact sequence of measurements to be made by any particular trainee is unknown, as are the hypotheses he is apt to generate at any given moment.

Reasons for Choosing Electronic Troubleshooting as SOPHIE's First Domain of Expertise

There were several factors that influenced our choice of electronic troubleshooting as the subject domain around which to build this system. The first is that it provides an excellent domain for developing and experimenting with a variety of training strategies. For example with the use of a simulator a trainee can experiment with a circuit by modifying its various components and examining the consequences of these modifications. Within the simulation context he can quickly make all kinds of measurements (some of which would ordinarily require the time-consuming operation of decoupling a component from the circuit). He need never worry about limiting his experimentation through fear of blowing up the instrument. Indeed if this happens, the trainee can be directly informed that his last experiment blew certain components or he could be told that something blew and be asked to troubleshoot his own mis-doings.

The second and by far the most important reason for choosing this domain is that the instructor in a typical laboratory setting seldom has the time to answer the individual questions which arise while the trainee is troubleshooting. Also the instructor doesn't usually have the time to have each trainee articulate the sequence of hypotheses that he is developing while troubleshooting. Consequently the instructor misses a crucial opportunity for providing the trainee with detailed logical analyses of correctness of his hypotheses just when he is most likely to benefit from such analyses! Note that an instructional system that has such inferencing or deductive capabilities has far more potential than just the obvious use of a simulator as first mentioned.

Protocol

The following protocol reveals some of the linguistic and logical capabilities of our current version of SOPHIE. We have included numerous annotations in the protocol thereby (hopefully) making it understandable to those readers not grounded in electronic terminology and fiction. In this session the trainee performs some measurements, develops a hypothesis and is told what is logically inconsistent with his hypothesis.

APPENDIX D

SUMMARY DATA ON COMPUTER-AIDED DESIGN PROGRAMS, PROGRAM DEVELOPERS, AND PROGRAM USERS

The data presented in this appendix was condensed from data presented in a 1975 Wright Patterson Air Force Base study conducted by Paul R. Owens, AFAL/TEA-4, Randall L. Ray, AFAL/TEA-4, and Dale L. Harper, AFAL/AAF-3.

The data is presented to provide an indication of the widespread and lively activity that exists in the field of automated design using computers. By no means should the data contained herein be construed to represent the total world of computer-aided design. As stated in the body of this report, it is estimated that over 1,100 computer-aided design programs are in use as of January 1978. This represents a substantial growth in the technology since the Air Force study of 1975.

TABLE D-1. USERS OF COMPUTER-AIDED DESIGN

ELECTRONIC AND AEROSPACE COMPANIES	SEMICONDUCTOR MANUFACTURERS	UNIVERSITIES	GOVERNMENT ORGANIZATIONS
Actron (McDonnell Douglas)	Advanced Memory Systems	Lincoln Laboratories (MIT)	Harry Diamond Lab.
Amdahl Corp	Advanced Micro Devices	Southern Methodist U.	Electronics Command (ECOM)
Bell Laboratories	Fairchild Semiconductor	Stanford University	Picatinny Arsenal
Bendix	Harris Semiconductor	U. of California (Berkeley)	Naval Electronics Lab.
Boeing Aircraft	Intel	U. of Florida	Naval Air Facility, IN.
Collins Radio	Motorola	U. of Southern California	AF Weapons Laboratory
Digital Equipment Corp	National Semiconductor		AF Materials Laboratory
General Dynamics, Ft Worth	Signetics		National Security Agency
General Electric	Texas Instruments		National Aeronautics & Space Administration
Hewlett Packard			Marshall Space Flight Center
Honeywell			Atomic Energy Commission
Hughes Aircraft Company			Sandia Laboratories
IBM			
Itek			
Litton Data Systems			
Lockheed-Georgia			
Lockheed Missiles & Space			
National Cash Register Co			
Philco Ford			
Raytheon			
RCA			
Rockwell International			
Singer-Kearfott			
Singer Librascope			
Sperry Univac			
Sylvania			
TRW			
United Aircraft Corp			
Westinghouse			

(Source: Owens, Ray, Harper, 1975)

TABLE D-2. SUPPLIERS OF COMPUTER AIDED DESIGN HARDWARE

Company	Hardware Produced
Applicon	Interactive Graphics Photoplotters
Calcomp	Photoplotters Line Plotters & Cutters
Calma	Interactive Graphics
Computervision	Interactive Graphics Photoplotters
David W. Mann, Inc.	Mask Pattern Generators
Electromask	Mask Pattern Generators
Gerber Scientific, Inc.	Interactive Graphics Photoplotters Line Plotters & Cutters
Gyrex	Mask Pattern Generators
M&S Computing	Interactive Graphics
Macrodata	Interactive Graphics
Xynetics	Line Plotters & Cutters

(Source: Owens, Ray, Harper, 1975)

TABLE D-3. ORGANIZATIONS PROVIDING COMPUTER-AIDED DESIGN SERVICES

ORGANIZATION	SERVICE
Algorex Data Corporation	PC Board and Hybrid Layout and Fabrication
Control Data Corporation	Time Sharing
Cosmic	Software Clearinghouse
Digitest	Software Consultation
National CSS, Inc.	Time Sharing
R/M Systems, Inc.	Software Consultation
RRC International, Inc.	Software Consultation
Silicon Systems, Inc.	LSI Chip Design
Softech, Inc.	Software Engineering
Systems Research Laboratories	Software Consultation
Ungerman Associates	Software Consultation
University Computing Company	Time Sharing

(Source: Owens, Ray, Harper, 1975)

TABLE D-4. COMPUTER-AIDED DESIGN CAPABILITIES OF SELECTED AEROSPACE AND ELECTRONICS SYSTEMS COMPANIES

								PC BOARD			LSI/HYBRID		
COMPANY	COMMON DATA BASE	CIRCUIT ANALYSIS	LOGIC SIMULATION	TEST PATTERN GENERATOR	FAULT DETECTION	FAULT ISOLATION	CHECK TOPOLOGY AGAINST LOGIC	AUTO PLACE	AUTO ROUTE	INTERACTIVE GRAPHICS EDIT/CREATE	AUTO PLACE	AUTO ROUTE	INTERACTIVE GRAPHICS EDIT/CREATE
Amdahl	1	2	2	0	2	2	0	2	2	0	2	2	0
Boeing	1	2	2	-	2	2	0	2	2	2	0	0	0
Bell Laboratories	0	2	2	-	-	-	0	-	2	2	2	2	2
Bendix	0	1	0	0	0	0	0	0	0	1	0	0	0
Collins	1	2	2	0	2	2	0	0	0	0	0	0	2
General Dynamics	0	0	0	-	-	-	1	-	2	1	0	0	1
General Electric	1,D	2	2	1	-	-	-	1	2	2	2	2	2
Honeywell	0	2	1,D	D	2	0	1	0	0	0	0	0	2
Hughes Aircraft	D	2	2	-	2	2	D	D	D	2	D	D	2
IBM	2	2	2	2	2	2	2	2	2	2	2	2	2
Itek	1	1	2	2	2	2	0	0	0	0	0	0	0
Litton	1	2	2	-	2	2	0	D	2	1	0	0	0
Lockheed-Georgia	0	0	0	1	2	2	0	0	0	0	0	0	0
Lockheed Missiles & Space	0	1	0	0	0	0	0	0	0	2	0	0	0
McDD (Actron)	1,D	2	2	-	-	-	0	0	0	0	2	2	2
Philco Ford	0	2	1	0	1	1	0	0	0	0	0	0	0
Raytheon	1,D	2	2	1	2	2	0	D	0	2	1	1	2
RCA	1,D	2	2	2	2	2	-	1	2	2	2	2	2
Rockwell International	1	2	2	-	2	2	0	1	2	2	0	0	2
Singer-Kearfott	0	2	2	0	2	-	0	D	2	2	D	D	2
Singer Librascope	1	-	1,D	0	1,D	1,D	0	D	1,D	2	0	0	0
Sperry Univac	1	2	2	2	2	2	0	0	2	2	0	0	0
Sylvania	0	2	2	1	1	1	0	0	0	0	0	0	0
TRW	D	2	D	D	D	D	2	0	0	0	2	2	2
United Aircraft	D	1	2	2	2	2	0	0	1	2	0	0	0
Westinghouse	1,D	2	2	-	2	2	-	0	2	0	2	2	0

2 = yes
1 = some capability
0 = no
D = in development

(Source: Owens, Ray, Harper, 1975)

TABLE D-5. CIRCUIT ANALYSIS SOFTWARE AND USERS

ACRONYM	USING ORGANIZATION(S)
AEDCAP	Raytheon
ALCAP	Rockwell International
ASAP	IBM
ASTAP	IBM
CIRC	Silicon Systems, Inc.
CIRCUS	Silicon Systems, Inc. Collins Radio Philco Ford
DCNL	Collins Radio
DICAP	Rockwell International
ECAP	Collins Radio Lockheed Missiles & Space United Aircraft Company Sperry Univac
FETSIM	RCA
FVAPC5	Collins Radio
MOSTRAN	Honeywell National Security Agency
MSINC	Standford University Silicon Systems, Inc. Army Electronics Command
NET-2	Harry Diamond Laboratories
PVAPC5	Collins Radio
RCAP	RCA
RECAL	RCA
SCEPTRE	General Electric Westinghouse Lockheed Missiles & Space Sylvania Sperry Univac Harris Semiconductor

TABLE D-5. LOGIC SIMULATION SOFTWARE AND USERS (continued)

ACRONYM	USING ORGANIZATION(s)
SCEPTRE (continued)	AF Aero Propulsion Laboratory AF Avionics Laboratory AF Materials Laboratory Sandia Laboratories Picatinny Arsenal
SNAP	National Semiconductor
SPICE (and its variations)	AF Avionics Laboratory Sandia Laboratories National Semiconductor Harris Semiconductor Texas Instruments Philco Ford Bell Laboratories Silicon Systems, Inc. University of California
TESS	TRW
TRAC	Silicon Systems, Inc. Sperry Univac Collins Radio
TRACAP	Rockwell International
TRANT	Advanced Memory Systems
UCCAP	Harris Semiconductor
WCAC5	Collins Radio

(Source: Owens, Ray, Harper, 1975)

TABLE D-6. LOGIC SIMULATION SOFTWARE AND USERS

ACRONYM	USING ORGANIZATION(S)
DIGISAT	Hughes Aircraft Company
D-LASAR	United Aircraft Itek
FAIRSIM	Fairchild Semiconductor
FANSIM	Sylvania
G-LASAR	Grumman Boeing
HAL1900	Philco Ford
LASAR	Lockheed-Georgia Naval Air Facility, Indianapolis
LATS	General Electric
LOGCAP	Harris Semiconductor
LOGIC	Westinghouse NSA TRW
LOGICBLOSSOM	Harris Semiconductor
LOGICSPEC	Singer-Kearfott
LOGSIM	RCA National Semiconductor Collins Radio Honeywell Harris Semiconductor National Security Agency NASA-Marshall Space Flight Center
SALOGS	Sandia Laboratories
SIMPAC	Sperry Univac
SIMSTRAN	Rockwell International
SIMULATOR	Raytheon
TEGAS	TRW Boeing Naval Weapons Laboratory
TIBSD	Texas Instruments

(Source: Owens, Ray, Harper, 1975)

TABLE D-7. PLACEMENT AND/OR ROUTING SOFTWARE AND USERS

ACRONYM	PLACE	ROUTE	TECHNOLOGY	USING ORGANIZATIONS
AEWRAP	0	1	Wire-Wrap	RCA
AIDS	1	1	Multi-Layer PC	General Electric
APAR (earlier) version is PR2D	1	1	MOS LSI	RCA Sandia Laboratories Marshall Space Flight Center ECOM TRW Actron
AUTODRAFT	1	1	Hybrids	RCA
CARI	0	1	Hybrids	Raytheon
CWRAP		1	Wire-Wrap	General Electric
MULTI		1	Multi-Layer PC	Westinghouse
PCCARDS	1	1	2-Layer PC	Harry Diamond Labs
PLINT	1	1	MOS LSI	General Electric
PRF	1	1	MOS LSI	Westinghouse National Security Agency
REDAL	1	1	2-layer PC	Boeing
WIRE		1	Wire-Wrap	Westinghouse

1 = yes

0 = no

(Source: Owens, Ray, Harper, 1975)

APPENDIX E

DESIGNER-ORIENTED CAD

TAEG Report No. 57

Designer-Oriented CAD

ZVONKO FAZARINC

Abstract—The philosophy and features of the designer-oriented computer-aided design (CAD) are presented and discussed from both the economic and technical standpoint. Dedication of the CAD system is proposed for efficient design with the minicomputer being the economical choice. Some novel techniques suitable for minicomputers are proposed and a CAD system tailored for designer-oriented operation is described. Based on a 16 k minicomputer, the system generates for each design problem a custom program containing a set of simulated test instruments, thus reproducing the familiar laboratory environment for the designer. A sample problem is given.

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I. Introduction

IT MAY NOT BE a popular undertaking to draw analogies between the present state of computer-aided design (CAD) and the early days of electronics. Nevertheless, it remains true that CAD places the engineer into a subordinate position by the mere fact that his time is less valuable than that of a computer. This strongly parallels the early era in which a similar unfavorable cost relationship forced engineers to compete for basic tools like oscilloscopes, voltmeters, and other test instruments. Until the advent of CAD, we have experienced a continuous decentralization of these design tools guided primarily by economic factors which favored increased efficiency of the

78 11 20 051

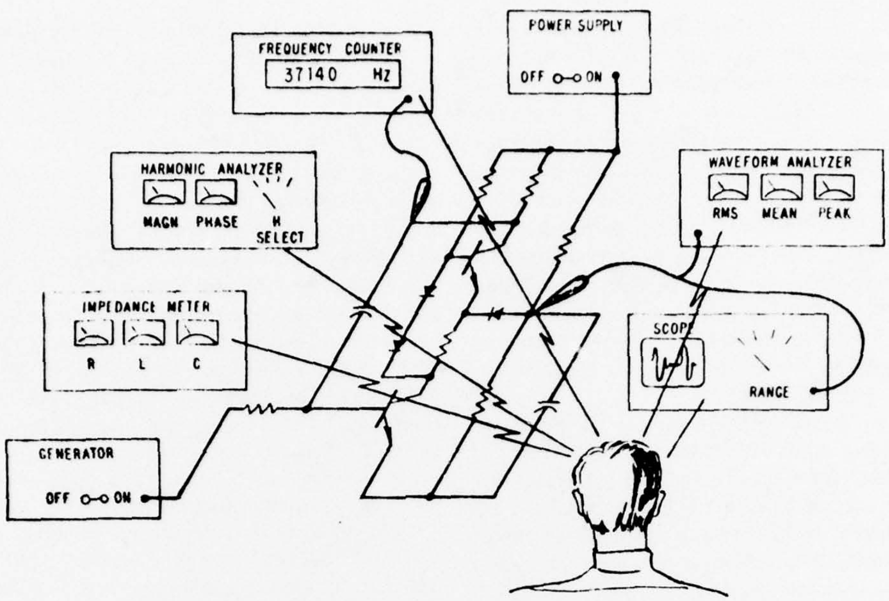


Fig. 1. Classical design process involves intimate interaction between the designer and his circuit.

designer over the efficient utilization of tools. CAD, however, relying on multimillion-dollar computer installations, forced a sudden reversal of economic priorities. Efficient utilization of computing power became the rule and the designer's interests had to be sacrificed. This observation is sustained by the fact that the engineer who wishes to avail himself of CAD must depart drastically from the established design methods, not merely because he is using a new medium but mainly because he cannot afford to use it any other way. Subsequently, we will refer to these prevalent implementations as "the computer-oriented CAD," as opposed to the "designer-oriented CAD." The latter is the subject of this paper, and will be explored from the economical as well as the technical viewpoint in subsequent paragraphs. A practical realization of a designer-oriented CAD system utilizing a minicomputer will also be described.

II. CAD and Classical Design

Every circuit designer uses his own specific technique to derive a topology from the performance specification. He may use his ability to synthesize a circuit, rely on his past experience with similar problems, or simply use a cookbook. Excluding this last case, we may safely assume that computers are not likely to make a significant contribution in this stage of circuit design for some time. The strength of CAD, though, lies in the second stage of circuit design in which the proposed topology is examined and the necessary changes are made to bring about conformity with the desired performance. Classically, this stage of design consists of wiring up the circuit and subjecting it to a series of measurements. These are intended to confirm the design predictions, but lead most often to a series of exploratory measurements indicated by the discrepancies. A large portion of the design effort is expended in this phase which is consequently dominated by the need for all available tools and aids. As illustrated in Fig. 1, the designer surrounds himself with a number of test instruments which are capable of giving him differing viewpoints of the same phenomenon, and thus allowing an easier and faster comprehension of the problem at hand. Subjecting the various inputs to mental processing, the designer forms a conclusion, takes action on his circuit, and then repeats the whole sequence as often as necessary.

It is important to realize that the described process is an incremental one in the sense that the step to be taken depends on the outcome of the previous action. Consequently, the type of information needed to form a new conclusion cannot be predicted and its availability on request is a vital ingredient of the classical design process. Relying on a complex mental process, an efficient design effort calls for a considerable degree of continuity over extended periods of time. A designer-oriented CAD system should then exhibit the following.

1) The continuous availability of information at the rate controlled by the designer.

2) The freedom to choose the origin and format of information about the circuit behavior.

There is another important aspect of classical circuit design which must be incorporated into a designer-oriented CAD system. It concerns the substitutional method employed by designers when dealing with large circuits or systems. Instead of attacking the whole complex at a time and making the task impossible for themselves, they will choose a relatively small portion of the network to be their design goal. The rest of the system, or parts thereof, are replaced by off-the-shelf units which only qualitatively meet the design goals and are needed to judge the performance of the circuit under design. The importance of this method cannot be overstressed since it not only allows the designer to focus his attention on selected parts of the whole system, but makes it possible to split the

design effort among more designers. To clarify this further, let us consider as an example the design of a heterodyne system, consisting of an oscillator, a mixer, and an amplifier. Suppose also that three designers are available. One of them will choose to design the mixer and will substitute a signal generator and a test amplifier for the missing oscillator and amplifier. The other two designers will also substitute some appropriate standard units for the missing circuitry and possibly trim them to bring their characteristics closer to those planned for the final units. During the course of design, the three designers may update and exchange information on the actual characteristics of their respective units and make additional trimming on their substitutes in the interest of easing the final interfacing problems.

A designer-oriented CAD system certainly should implement the substitutional capability for reasons listed above and also for an additional reason specific to CAD. If blocks of a large circuit can be entered by simplified descriptions and can also be properly linked to the topology under consideration, significant savings in the required memory capacity, as well as the computation time, accrue. We may list, then, our third desirable property of a designer-oriented CAD system as follows.

3) The acceptance of global descriptions of blocks linked to standard topological inputs.

III. Economic Considerations

In the Introduction we pointed out that the existing computer-oriented CAD implementations were dictated by economic priorities. This becomes understandable if the relative costs of central processing unit (CPU) and designer time are compared. Ratios of 50 to 100 are typical for batch-type operations and are higher in a time-shared environment. A designer-oriented implementation may be difficult to defend under these conditions since a one-percent increase in computer time wipes out the designer's share of the total design fund. How then can we talk about designer-oriented features described in the previous section if we realize that feature 1), for example, implies equal times for designer and computer, or at best a limited amount of time-sharing? (In order to keep the overall design cost at the same level, the designer's job would have to be done 100 times faster, which is not a realistic expectation even for a designer-oriented CAD system.) Furthermore, feature 2) calls for peripherals somewhat more sophisticated than a teletype and data transfer rates above those commonly handled by telephone lines.

A dedication of the system with instantaneous availability of input–output channels with direct program control seems almost inevitable for a full-scale designer-oriented implementation. This course, however, leads away from large computer installations in search of a suitable system compatible in running costs to a designer. If such a CAD system cuts the total design time in half, the computer cost has been fully recovered; it is the contention of CAD proponents that time savings of at least that much can be expected from a conventional CAD. It is the contention of the author that a designer-oriented CAD can do even better. Accepting this premise, we may then conclude that a computer system costing about ten dollars an hour would be economically justifiable for a dedicated CAD operation. This can be translated into an initial purchasing cost of 45 000 dollars for the complete system if a 5-year amortization schedule is applied, if 20 percent of the total cost is assigned to maintenance, and if the system usage per month is 100 h. The amount of 45 000 dollars can purchase a 32-kbyte minicomputer interfaced to a 5-Mbyte disk, a teletype, and a simple plotter. The speed may approach that of an IBM 360/50 computer. This may fail to meet the speed requirement of a modern CAD system by a factor of 10 to 20 and the memory requirement by a factor of 2 to 4. Direct translation of an existing CAD program for minicomputer operation is then out of the question, as the example of ECAP II illustrates. Translated for the 1130 minicomputer, the program requires 15 s to compute one point for a 30-branch circuit [1]. Based on the experiences of the author, this is between two and three orders of magnitude slower than called for by our continuity requirement 1).

While the minicomputer meets the price tag of a dedicated CAD, it challenges our inventiveness to find new techniques that may effectively offset the minicomputer's weaknesses. The development of these techniques must go hand in hand with the introduction of designer-oriented features.

IV. Technical Considerations

During the execution of a standard CAD program, there is a minimum amount of code which must be resident in core, regardless of the circuit size. This amount is significantly larger than that which is left of the 16 000 words of our imaginary minicomputer after the operating system has been accommodated. The addition of conveniences expected in a designer-oriented system makes the situation even worse. On the other hand, we know that it is possible to write a set of circuit equations for a specific circuit in, say, Fortran language, and then fit the whole program easily into a few thousand words of core. Moreover, once the basic memory needs for the library routines have been satisfied, the circuit equations use very little extra memory in comparison.

A. Custom Program for Each Problem

Writing a custom program for each specific circuit problem is exactly what we are proposing for a minicomputer CAD, with the distinction that we teach the computer to write the program. The reader can appreciate the freedom a source language program offers in extending the scope of computerized analysis beyond what is available in a commercial CAD. He also will appreciate the execution phase efficiency of such a program. No sophisticated techniques invented for an efficient CAD can compete with a custom-written program which contains only a set of statements reflecting the Kirchhoff's laws applied to the particular circuit, and hence are subject to a minimum amount of overhead. Moreover, a source language program enables one to incorporate global descriptions of blocks linked to circuit equations by means of the symbology provided by the particular language. This makes possible, in a most elegant way, the implementation of the substitutional method discussed in Section II, feature 3). Finally, the inclu-

sion and description of nonlinearities becomes trivially simple in the presence of symbolic circuit equations if certain conventions are adopted. The advantages of a source language program are so numerous that they far outweigh its drawbacks, which we examine next.

A source program must be compiled before its execution can commence. This is the price we have to pay unless we are willing to run interpretively and sacrifice the efficiency. During compilation, the link between the symbology introduced by the user and the machine language equivalent is lost. This link must be restored if the designer is to have easy access to all parameters of his circuit during execution. A significant drawback of a compiled program is the need for prescheduling of inputs and outputs. This is in direct conflict with our most important designer-oriented feature 2) which calls for free selection of input–output channels. This and the restoration of symbolic links are, then, two areas which need attention. Since there are many possible ways to deal with them, however, we will not make any generalizations.

B. Generation of Circuit Equations

At this point we will examine the techniques for generation of efficient circuit equations.

The A-matrix circuit description introduced in 1957 by Bashkow [2], and later expanded by Bryant [3], [4], Wilson and Massena [5], and Kuh and Rohrer [6], provides a systematic link between the Kirchhoff's laws and the corresponding topology given in terms of interconnections of circuit elements. Fig. 2 sets down our chosen notation and provides the link to [6].

A novel partitioning of the F-matrix illustrated in Figs. 3 and 4 is proposed. It results in significant savings of memory space and computation time and provides additional information to the designer. The savings is realized for a broad class of topological connections which are commonly encountered in practice.

The matrix of link resistors with entries opposite V_S and C_B has been denoted by R_{CV} and their corresponding current vector by I_R. The remaining link resistors are lumped in the matrix R_L and are treated in the conventional way. The symbols in parentheses identify the circuit variables which we may wish to compute explicitly. All other branch and link variables, except for link capacitor currents, can be expressed in terms of those in parentheses by simple algebraic operations.

Following closely the elimination procedure outlined in Kuh and Rohrer [6], but modified for the proposed partitioning of the link resistor matrix, one can derive the following set of matrix equations for the desired circuit variables (refer to Figs. 3 and 4 for the notation):

$$I_V = -F_{VR} \cdot R_L^{-1} \cdot F_R^T \cdot \begin{bmatrix} V_S \\ V_C \\ V_R \end{bmatrix} - F_{VI} \cdot \begin{bmatrix} I_R \\ I_L \\ I_S \end{bmatrix} \tag{1}$$

$$\frac{d}{dt}(C \cdot V_C) + F_{CR} \cdot R_L^{-1} \cdot F_R^T \cdot \begin{bmatrix} V_S \\ V_C \\ V_R \end{bmatrix} = -F_{CI} \cdot \begin{bmatrix} I_R \\ I_L \\ I_S \end{bmatrix}, \quad C = C_B + F_C \cdot C_L \cdot F_C^T \tag{2}$$

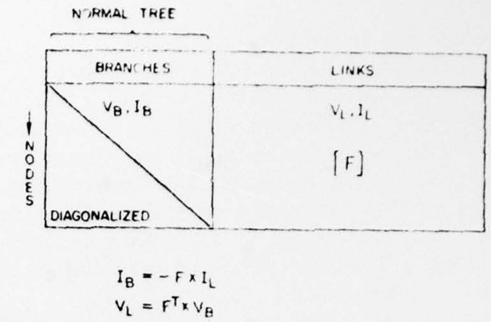


Fig. 2. Diagonalized incidence matrix produces the normal tree and the F-matrix.

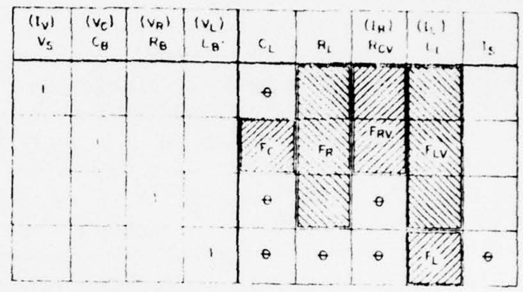


Fig. 3. New partitioning of the F-matrix distinguishes two classes of link resistors: R_L and R_{CV}.

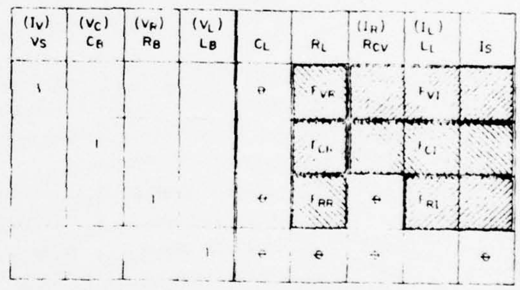


Fig. 4. Proposed row partitioning forces the link resistor current I_R into the current source vector.

$$\left[\begin{bmatrix} 0 & & \\ & 0 & \\ & & 1 \end{bmatrix} \cdot R_B^{-1} + F_{RR} \cdot R_L^{-1} \cdot F_R^T \right] \cdot \begin{bmatrix} V_S \\ V_C \\ V_R \end{bmatrix} = -F_{RI} \cdot \begin{bmatrix} I_L \\ I_S \end{bmatrix} \tag{3}$$

$$V_L = \frac{d}{dt}\left([M_{LB}^T - [L_B + M_{BB}] \cdot F_L] \cdot I_L \right) \tag{4}$$

$$I_R = R_{CV}^{-1} \cdot F_{RV}^T \cdot \begin{bmatrix} V_S \\ V_C \end{bmatrix} \tag{5}$$

$$\frac{d}{dt}(L \cdot I_L) = F_{LV}^T \cdot \begin{bmatrix} V_S \\ V_C \\ V_R \end{bmatrix}, \quad L = L_L + M_{LL} - M_{LB} \cdot F_L - F_L^T \cdot M_{LB}^T + F_L^T \cdot [L_B + M_{BB}] \cdot F_L \tag{6}$$

where

M_{LL} link-to-link mutual inductance matrix;

M_{BB} branch-to-branch mutual inductance matrix;

M_{LB} link-to-branch mutual inductance matrix.

Equations (1)–(6) are general and complete and they define all quantities of interest, including the link resistor current vector I_R. They can be applied to either linear or nonlinear circuits and to dc, ac, or transient analysis. (Let it be mentioned here that the concept of dc analysis is not part of the classical design vocabulary, but was introduced as an ingredient of the computer-oriented CAD.)

The need for CAD is concentrated in the area of nonlinear circuits because they are not accessible to continuous analysis and they continue to draw the attention of integrated circuit designers who view CAD as a powerful substitute for breadboarding. It is therefore felt that transient analysis should be the basis of designer-oriented CAD, but should also offer large-signal steady-state analysis applicable to nonlinear circuits. This is a concept foreign to present CAD implementations, but commonly used by practicing designers. It allows, for example, the definition of equivalent large-signal impedance of a nonlinear circuit for matching purposes or the distortion analysis of an amplifier or oscillator. Wave analyzers, vector voltmeters, and similar test instruments are used in performing the relevant measurements in the classical design environment. Their function can be simulated in CAD by Fourier analysis of time-domain waveforms. We will touch upon this subject in part D of this section.

C. *Numerical Integration*

Transient analysis requires the solution of differential equations (2) and (6). The integration schemes employed to perform this function can influence the execution time to a large extent, and were therefore given special attention.

The Euler integration formula—the simplest of all integration algorithms, which was rejected many times in the past because of its divergent character [7]–[9]—was reexamined and it was found that by a slight modification it can be made not only convergent, but also long-term stable. This is an important property for a designer-oriented CAD which may be subjected to extended periods of operation. The theoretical basis of modification was reported elsewhere [10], and only the result is summarized here. If an mth order system can be described by the state equation

$$\dot{x}(t) = A \cdot x(t)$$

then the application of the forward Euler formula yields the solution

$$x(t + \Delta t) = [I + A \cdot \Delta t]\, x(t) \qquad (7)$$

where $x(t)$ is the state vector, I is the identity matrix, and A is the circuit's A-matrix. The above scheme produces divergent solutions for m larger than one, regardless of the size of the integration time interval Δt. The following modification of the ith row of (7) produces long-term stable solutions for any m, provided that Δt is chosen to be shorter than the shortest natural period of the system:

$$x_i(t + \Delta t) = [I + A\Delta t]_i \begin{bmatrix} x_1(t + \Delta t) \\ x_2(t + \Delta t) \\ \cdot \\ \cdot \\ \cdot \\ x_{i-1}(t + \Delta t) \\ x_i(t) \\ \cdot \\ \cdot \\ \cdot \\ x_m(t) \end{bmatrix}. \qquad (8)$$

In simple terms, the scheme of (8) consists of a sequential rather than a simultaneous integration of state variables. Being explicit, the formula is extremely simple to implement for nonlinear systems by an updating of all nonlinear constraint equations once every time step Δt. Furthermore, the formula can be very naturally employed in the framework of a source language which we have proposed in part A.

The integration formula (8) is explicit, and as such becomes numerically unstable when the time interval Δt exceeds the shortest natural period of the system. Implicit formulas, on the other hand, keep the solutions within bounds, and therefore are considered to be the cure for the stiff-system problem [11]–[13]. In effect, the sampling theorem is violated when the time step exceeds half the natural period. The penalty we pay for that is the instability in explicit formulas and the presence of error terms unrelated to continuous solution in implicit schemes. These error terms may be negligible in many cases, but are disturbing and are accepted only as an alternative to excessive computer bills. Based on economies expounded in Section III, one might consider the possibility of never violating the sampling theorem. In this case, the simplest possible explicit integration formula represents the best choice. Equation (8) is in that category and is, in addition, more accurate than the most popular implicit scheme—the trapezoidal formula—for systems beyond order one [10].

A final word in defense of explicit numerical integration formulas. When the shortest period in a system is that of the excitation, then one does not have the choice of not obeying the sampling theorem regardless of the formula applied. The frequency-mixing circuits, parametric amplifiers, synchronous detectors, and the like fall into this category. Being notorious consumers of computer time, these circuit problems are best served by an efficient integration formula of the explicit nature.

D. *Simulation of Test Instruments*

We have concluded in Section II that the choice of the information origin and format should be left to the designer. Obviously, all possible choices must be built into a designer-oriented CAD system and left idle until called upon. A medium of interaction must be set up which is constantly monitored by

the computer and which can be influenced by the designer. In our dedicated "hands-on" system, the sense-switch register may provide such a medium—the state of which can be checked with negligible overhead every time the time loop is executed. Other solutions are possible, so we postulate the existence of some interactive medium for selection by the designer of both the origin and domain of information and discuss the generation of the latter.

Most commonly encountered in the repertoire of test instruments on the designer's bench is the oscilloscope. It is employed more as a qualitative than as a quantitative tool since it is capable of transferring huge amounts of qualitative information to the user in a relatively short time. Few designers are willing to trade their oscilloscope for a table of numbers representing the same waveform, regardless of the number of decimal places carried. They will not settle even for a plot if there is a considerable delay between their action and the availability of the plot. A serious design process is very sensitive to disruptions of continuity, and the whole fragile structure built from pieces of information and leading towards a conclusion may dissolve into nothing if the last missing building block arrives too late.

It is felt that the waveforms should be made available as they are computed point by point via a digital-to-analog converter in the form of a graph or a CRT display. Besides meeting the designer's approval, such an arrangement does away with the need for storage of large blocks of data, as is often done in present implementations. Equations (1)–(6) in combination with (8) provide all state variables plus some extra waveforms at every time interval. Also, any block descriptions or other definitions added by the user are available continuously and the designer may choose any of them by means of the interactive medium to appear on the plotter or the screen. The analogy to an oscilloscope with a movable probe hardly can be denied to such an arrangement.

We have mentioned earlier the need for steady-state analysis of nonlinear circuits achievable via the Fourier analysis. The concept is straightforward in principle, so let it only be mentioned that the harmonic number and the waveform selection may be done through the interactive medium and that Fourier analysis may proceed concurrently with the integration of circuit equations by a second integration of weighed samples. The desired outputs are magnitude and phase which can be derived from integrated samples once every period of the fundamental frequency. Such outputs also may be combined for various waveforms into transfer or driving-point impedances, S-parameters, or the like. If so, the designer again should have a free choice to select the particular combination.

Fourier analysis may tax the execution time if the required sine and cosine functions needed to weigh the samples are derived from the library routines. Since the argument is not random, but follows a well-defined pattern, more efficient algorithms should be employed. One derived from [10, eq. (7)] provides savings of 20 times in computation time when compared with typical trigonometric algorithms found in program libraries.

In addition to simulating a synchronous detector, vector voltmeter, wave analyzer, and impedance meter, the integrator of a Fourier-analyzer routine also can be used to simulate a signal averager and rms meter.

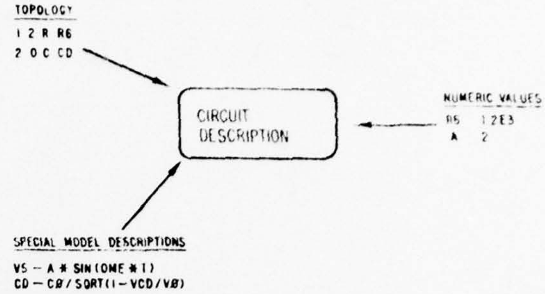


Fig. 5. Three phases of circuit description in the Hewlett-Packard CAD system.

Not uncommon objects to be designed are free-running circuits like oscillators, multivibrators, etc. The designer in control of the CAD system may want to apply a simulated frequency counter to some point in the circuit and extract the frequency of oscillation. This then may be fed to the Fourier analyzer as the fundamental frequency, making the distortion analysis of the oscillator signal possible, or the frequency itself may be plotted as function of time. The latter application of a simulated counter is illustrated in the example of Section V.

Time-domain waveforms contain all the information one can gather about a given circuit. It all can be displayed on the screen of an oscilloscope; nevertheless, a whole array of test instruments is being used by designers to convert this same information into other forms for convenience and efficiency. Simulation of test instruments in CAD systems should be considered in this light.

V. Designer-Oriented CAD System

A CAD system based on ideas presented in previous sections has been developed for internal use at the Hewlett-Packard Company. It was designed around the disk-operating system using a 2100A minicomputer with 16 000 words of memory. It is capable of generating for each particular circuit a custom program containing the circuit's symbolic equations in Algol source language. The equations are generated from a topological description in which every component is given a symbolic name rather than a numeric value (see Fig. 5). A component name preceded by the letter V is interpreted as the voltage across that component and the prefix I identifies the current through it. This convention enables the user to communicate with the computer not only in terms of component names, but also in terms of circuit variables. Consequently, he can enter algebraic descriptions of components, blocks, models, etc., in terms of circuit variables and be assured that these will be interpreted by the computer as intended. (With this capability it is obvious that the distinction of dependent and independent sources becomes unnecessary during the topological specification.)

The equations generated by the Hewlett-Packard CAD system and the equations entered by the designer are distributed

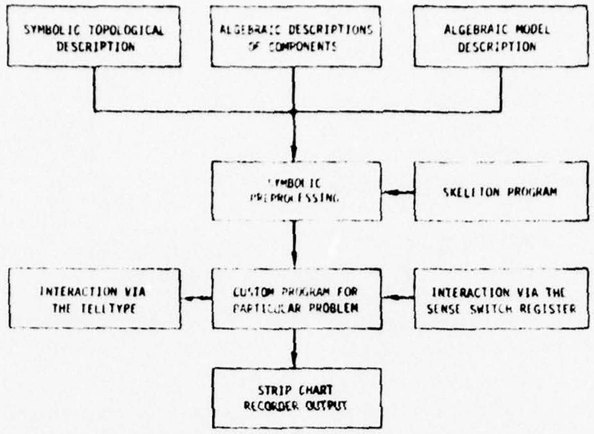


Fig. 6. Generation of the source program in the Hewlett-Packard CAD system.

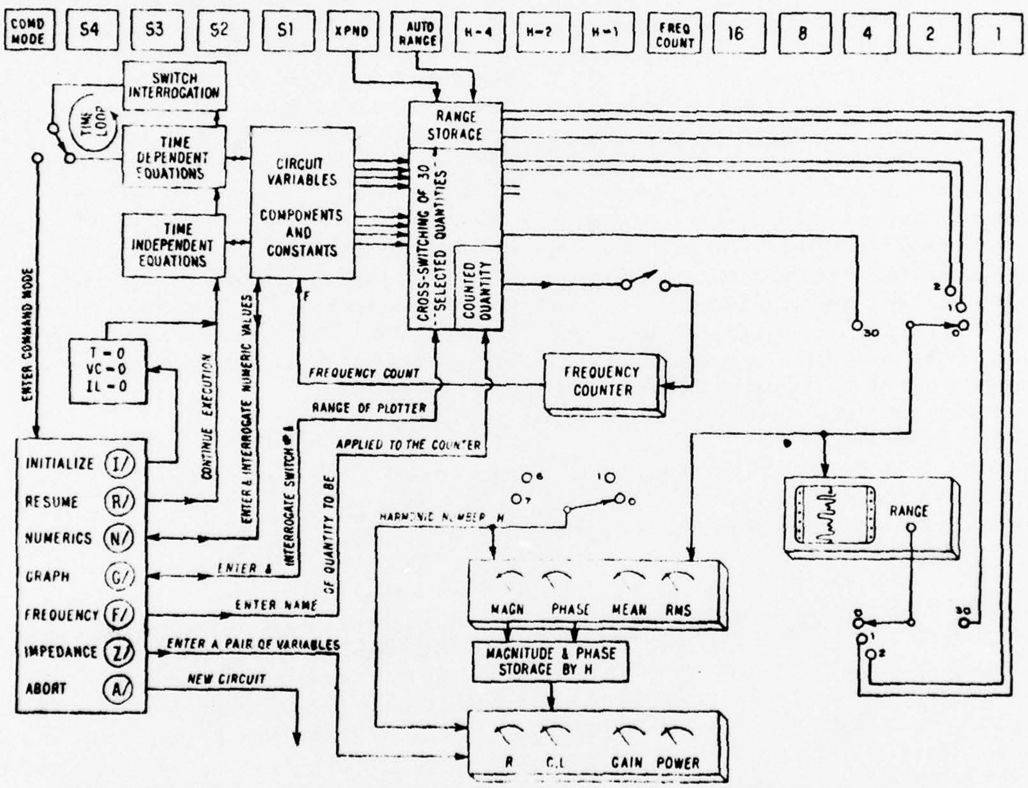


Fig. 7. Block diagram of the executable custom program generated by the Hewlett-Packard CAD system.

within a skeleton program as indicated in Fig. 6. The distribution process optimizes the custom source program with respect to execution time by imbedding within the integration loop only time-dependent equations; the remaining equations are placed in an area which is executed only when a numeric value is changed by the designer. The skeleton program itself contains a number of branching points conditional on the state of the sense-switch register on the computer console.

A schematic diagram of the custom program is shown in Fig. 7 and its equivalent in Fig. 8. The sense switches are shown at the top. Switches 1-16 function like a moveable probe which picks up a particular variable and feeds it to the strip-chart recorder—the principal output device of the system.

Switch FREQ COUNT activates a simulated frequency counter which derives once for every period the frequency of a periodic signal applied to it.

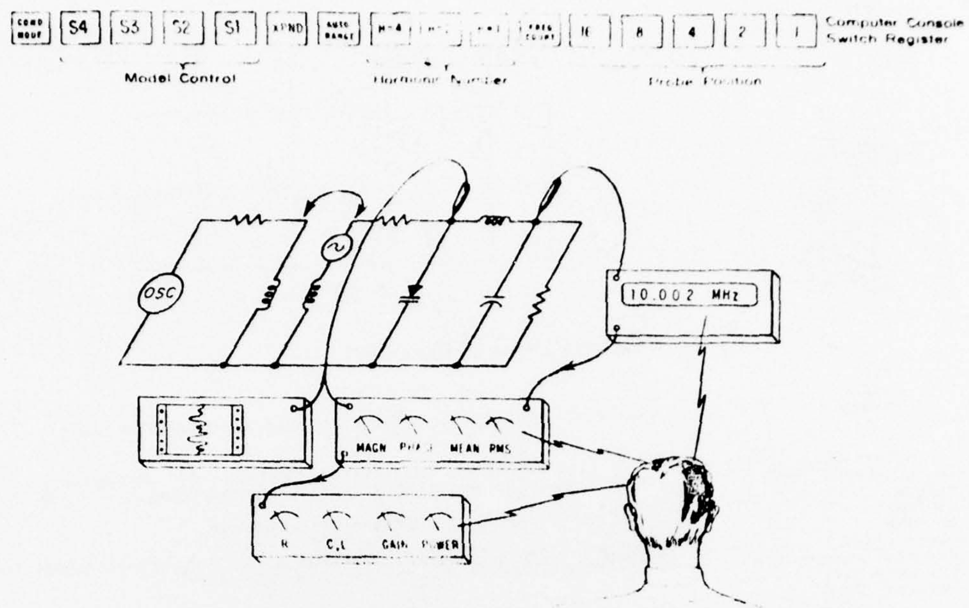


Fig. 8. Hewlett-Packard CAD system simulates the classical design process.

Switches H = 1-H = 4 select harmonic numbers (up to 7) and apply the Fourier analyzer to the signal selected by switches 1-16.

The AUTO RANGE switch causes automatic adjustment of the plotter limits to the largest excursions of the signal, while the XPND switch expands the time axis resolution by a factor specified by the user.

*S*1-*S*4 are reserved for circuit control, and their use is demonstrated in the example at the end of this section.

The COMND MODE switch interrupts the simulation loop and makes accessible at the teletype a number of commands. Their function is indicated in Fig. 7 and their usage is also illustrated in the example.

The time needed to generate the custom program takes only seconds during which time eight separate overlays are brought from the disk into core and executed. It typically takes a few minutes to produce the final absolute executable program. The whole sequence is executed automatically and does not require familiarity with the operating system. The executable program is core resident and does not require the presence of the disk. It is also at this point that numeric values are demanded for components and constants introduced earlier. These can be changed at any later time in the command mode, but the simulation cannot be started until all values are specified.

The mixer circuit shown in Fig. 9 is used to demonstrate the usage of the Hewlett-Packard system. Underlined portions of the text are those typed by the user. The author's comments are typed in block letters, and the remaining text is printed by the system. Symbolic circuit equations are optional and may be suppressed by the user.

Some of the simulation results are presented in Fig. 10; plotted as functions of time for various states of the switches *S*1 and *S*2 are the oscillator voltage *V*1, the oscillator frequency *F* (measured with the simulated frequency counter), the diode voltage *VD*1, and the output signal *V*6. Build-up of oscillator voltage and the accompanying drift of frequency are two of the many interesting details brought out by the simulation. Others are the onset of rectification and dc bias build-up after *S*1 was actuated, the appearance of the difference frequency signal at the filter output following the activation of *VS*, and, finally, the modulation of the oscillator amplitude and frequency at the difference rate.

Waveforms appearing in Fig. 10 were generated and plotted on line with 2000 points per major division. Computing all circuit variables at one point in time required 17.5 ms. Each period of the oscillator signal *V*1 is represented by approximately 180 points, or 3 s of generation time. The output rate could be increased by a factor of up to ten, but would not be considered convenient by the designer.

The example chosen is not representative of the complexity of problems that the Hewlett-Packard CAD can handle. With 16 000 words of memory, 100 branches, and 50 algebraic equations can be accommodated in addition to the disk-operating system. Work is presently underway to at least double this capacity.

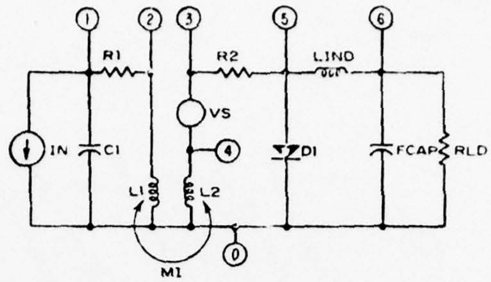
VI. Conclusions

High cost of computing dictates a number of compromises in CAD which diminish the efficiency of the designer. Some of these are based on false economy, as for example lack of interactive capabilities between the designer and the computer. If

```
•••HEWLETT-PACKARD•••
••COMPUTER-AIDED DESIGN••

READ SEC 1.

NAME: MIXER
    1:  1 0 I IN
    2:  1 0 C C1
    3:  1 2 R R1
    4:  2 0 L L1 MI
    5:  3 4 V VS
    6:  4 0 L L2 MI
    7:  3 5 R R2
    8:  5 0 D D1
    9:  5 6 L LIND
   10:  6 0 C FCAP
   11:  6 0 R RLD
   12:  END
```



COMPUTER GENERATED EQUATIONS

```
V1-VC1;
V2-VC1-VR1;
V3-VD1+VR2;
V4-VD1-VS+VR2;
V5-VD1;
V6-VFCAP;
```

ALL NODE VOLTAGES ARE DEFINED IN TERMS OF BRANCH VOLTAGES.

```
IRLD-(VFCAP)/RLD;
ID1--IL2-ILIND;
IVS-IL2;
```

SOME LINK AND BRANCH CURRENTS ARE DEFINED. "I" PRECEDING A COMPONENT NAME SYMBOLIZES THE CURRENT THROUGH THAT COMPONENT.

```
XGR1-1/R1;
XGR2-1/R2;
```

SOME CONDUCTANCES ARE DEFINED FOR LATER USE.

```
C1*VC1'--IN-IL1
FCAP*VFCAP'--IRLD+ILIND
(XGR1)*VR1-IL1
(XGR2)*VR2--IL2
```

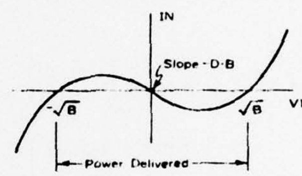
"V" PRECEDING A COMPONENT NAME SYMBOLIZES THE VOLTAGE ACROSS THAT COMPONENT. APOSTROPHE DENOTES TIME DERIVATIVE.

```
L1*IL1'+MI*IL2'-VC1-VR1
MI*IL1'+L2*IL2'-VD1-VS+VR2
```

COUPLED DIFFERENTIAL EQUATIONS ASSOCIATED WITH MAGNETIC COUPLING.

```
LIND*ILIND'--VFCAP+VD1

READ SEC. 2.
    1:  IN-D*(V1↑3-B*V1)
    2:  IF S1 THEN MI-K*SQRT(L1*L2) ELSE MI-0
    3:  OME-2*PI*FRQ
    4:  IF S2 THEN VS-A*SIN(OME*T) ELSE VS-0
    5:  END
```



1. IN IS DEFINED TO BE A FUNCTION OF THE VOLTAGE ACROSS IT. AT LOW LEVELS OF V1 IN SUPPLIES CURRENT INTO THE TANK CIRCUIT AND DRAWS FROM IT WHEN |V1| EXCEEDS $\sqrt{B}$. A VAN DER POL TYPE OSCILLATOR RESULTS. $(IN = D\cdot(V1^3 - B\cdot V1))$.
2. COUPLING BETWEEN L1 AND L2 IS PRESENT ONLY IF THE SWITCH S1 IS ON. MI IS DEFINED IN COMMON TERMS AND WILL BE RECALCULATED FOR EACH CHANGE IN THE VALUES OF EITHER L1, L2 OR THE COUPLING COEFFICIENT K. VALUE FOR MI WILL NEVER BE REQUESTED.
3. RADIAN FREQUENCY OME IS DEFINED IN TERMS OF FRQ. ONLY THE NUMERIC VALUE FOR FRQ WILL BE REQUESTED.
4. VOLTAGE SOURCE VS IS DEFINED TO BE SINUSOIDAL OF FREQUENCY FRQ AND AMPLITUDE A. IT CAN BE TURNED ON AND OFF WITH THE SWITCH S2.

ENTRY OF SOME NUMERIC VALUES

```
READ SEC. 3
N/
```

DT 5E-11	INTEGRATION TIME STEP SET TO 50 PS.
C1 2-11	OSCILLATOR CAPACITOR, 20 PF.
L1 1E-7	OSCILLATOR INDUCTOR, 0.1 µH.
LIND 1-5	FILTER INDUCTOR, 10 µH.
FCAP 5-11	FILTER CAPACITOR, 50 PF.
RLD 1000	LOAD RESISTOR, 1000 OHMS.
CJ0 1-11	DIODE ZERO BIAS CAPACITANCE, 10 PF.
TAU 1-9	DIODE BASE TRANSIT TIME, 1 NS.
IST 1-13	DIODE SATURATION CURRENT, 0.1 PA.
RDB 1	DIODE BULK RESISTANCE, 1 OHM.
FRQ 1+8	VOLTAGE SOURCE FREQUENCY, 100 MHz.
D .0002	CURRENT SOURCE CONSTANT, 0.0002.

ASSIGNMENT OF OUTPUT SWITCHES

```
G/
```

F 8 126E6 86E6	F ON SWITCH 8. LIMITS: 126 MHz, 86 MHz.
V1 1 6 -34	V1 ON SWITCH 1. LIMITS: 6 VOLTS, -34 VOLTS.
V6 6 .14 -.06	V6 ON SWITCH 6. LIMITS: 0.14 VOLTS, -0.06 VOLTS.
VD1 3 5.5 -4.5	DIODE VOLTAGE ON SWITCH 3. LIMITS: 5.5 VOLTS, -4.5 VOLTS.

Fig. 9. Example of the mixer in which block description is linked to the topology using the symbolic convention.

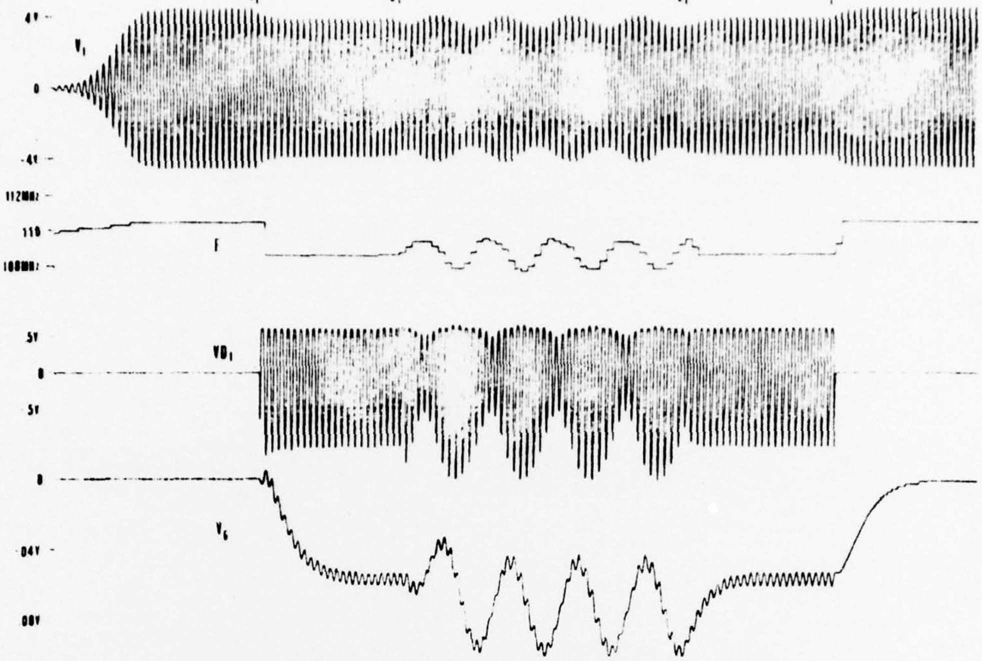


Fig. 10. Results of simulation of the circuit shown in Fig. 9.

the computer were forced to continuously report on the progress of computation and the designer were given the chance to interact, many potentially unsuccessful runs could be terminated in their early stages. Another example is the rigidity in problem specification format. If the designer were given more freedom in this area, he could decide to describe a large conglomerate of circuit components by simple block descriptions, again resulting in significant savings. These two features which offer at least partial economic justification plus many others which represent almost exclusively designer's interests can be incorporated in a dedicated system and be truly economical if based on high-performance minicomputers. New techniques may help these systems achieve high standards today and provide realism to future CAD which is viewed by this author as just another self-contained electronic instrument on the designer's bench. In the process, the role of large CAD installations will be either reduced to prescheduled analyses of large systems which were designed elsewhere or be phased out completely. The fact that the pocket calculators HP-35 and HP-80 which contain equivalents of 30 000 and 40 000 transistors, respectively, were designed exclusively on minicomputers tends to support such a prediction.

Acknowledgment

The ideas presented in this paper would have remained just that without the active support of ERL director, Dr. P. Stoft, who believed in their feasibility and encouraged their realization. His familiarity with the major obstacle led to the hiring of K. Van Bree, who has expertly laid the groundwork for symbolic processing of circuit topology. K. Stockwell extended this initial effort and made vital contributions in all phases of the Hewlett-Packard CAD development. I. Radvany has provided the necessary software for interface with the disk-operating system and has assisted in other areas. Dr. J. Duley and J. Welsch have lent their software expertise on many occasions, and their valuable contributions are gratefully acknowledged.

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